AD/A-006 123

RAIN ATTENUATION STUDIES

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Prepared for:

Air Force Cambridge Research Laboratories

March 1973

UNCLASSIFIED
Security Classification

AD/A-006 123

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) McGill Radar Weather Observatory P.O. Box 241, Macdonald College, P.Q., Canada	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

RAIN ATTENUATION STUDIES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific. Interim.

5. AUTHOR(S) (First name, middle initial, last name)

G. Drufuca

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1973	105	14

8a. CONTRACT OR GRANT NO. F19628-73-C-0052 b. PROJECT NO. Task No., Work Unit No. 6672-03-01 c. DOD Element 62101F d. DOD Subelement 686672	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFCRL-TR-73-0352

10. DISTRIBUTION STATEMENT

A- Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES TECH, OTHER	12. SPONSORING MILITARY ACTIVITY Air Force Cambridge Research Laboratories L. G. Hanscom Field Bedford, Massachusetts 01730

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rain attenuation						
Communications						
Microwave link						
Weather radar						
Radar Climatology						

AFCRL-TR-73-0352

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Contract No. F19628-73-C-0052
Project No. 6672
Task No. 667203
Work Unit No. 66720301

Scientific Report No. 3

March 1973

Contract Monitor: Albert C. Chmela
Meteorology Laboratory

Approved for public release; distribution unlimited

Prepared
for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

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PREFACE

The aim of this report is to collect in one place and in printed form the results of three years of work on rain attenuation statistics. Nothing, or close to nothing, has been done here toward the explanation or rational interpretation, of these results in terms of storm modelling or climatology, although these results contain much information on these topics. These results should just be consiedered for what they are: observations of the precipitation process translated in a form suitable for the planning of radio systems across Canada.

I am grateful to the Atmospheric Environment Service for rainguage and upper-wind data, and to McGill Radar Weather Observatory for radar records. (The basic radar there is on loan from the Air Force Cambridge Research Laboratories under their contract F19628-73-C-0052.)

I wish to acknowledge the contribution of Mr. Chul-Un Ro who carried on the analysis of the rainguage data for Montreal and the other locations in Canada during his work toward a Master's degree in Meteorology.

I am deeply indebted to Prof. J.S. Marshall and to the other members of the Stormy Weather Group; in particular to my friends Dr. R.R. Rogers and I. Zawadzki who had many suggestions and useful criticisms. Dr. K.S. McCormick and D.S. Strickland of CRC (which supported the work) have been most helpful and understanding.

Mr.Daniel Salomon did all the computer work and his contribution is greatly appreciated.

RAIN ATTENUATION STUDIES

Scientific Report MW-77

Volume I

CONTENTS

1. INTRODUCTION

For the planning of radio systems making use of frequencies above 10 GHz the knowledge of the statistical properties of rain attenuation which dominate the propagation at these frequencies is required.

The basic parameter in the design of a radio system is the outage time of the system which can be due to various causes, among which is attenuation by rain. The outage time due to rain attenuation depends on the possibility of the system to recover from the noise on attenuated signal. This possibility is limited to a given threshold, which is a function of the system characteristics. The outage time is then the total time for which the rain attenuation exceeds this threshold.

This work attempts to describe the statistical properties of the time for which rain attenuation exceeds a given value as a function of the frequency and the hop length. These properties are studied for three frequencies (11.2; 12.7; 18.76 GHz) and various hop lengths (2.5; 5; 7.5; 10; 12.5; 15 mi). Results are given for six locations across Canada. They are: Edmonton, Winnipeg, Thunder Bay, Toronto, Montreal and Halifax.

Two approaches have been used, the first, described in chapter 2, makes use of the McGill weather radar data for 1971, jointly with the data of an experimental link at 11.2 GHz installed by BNR in Ormstown (fig. 1). In this experiment the radar data of the summer 1971 have been used to simulate the attenuation process over a dense network of links of various lengths, and the observed statistics from the BNR link have been used to calibrate the simulation. This experiment has given unique information about extreme events, and thanks to the very large sample size of the data, events with probability of $\sim 10^{-8}$ have been evaluated. Further it has provided unique information about joint probabilities of attenuation for parallel links such as required for the design of twin route systems.

A second approach, described in chapter 3, consists in the development of a method of simulating the attenuation process from raingauge records and radiosonde data. The method is based on the concept of a synthetic storm first introduced by Hamilton and Marshall. The method has been tested with the aid of the McGill Weather Radar and the BNR link and then applied to ten years of data for the six locations across Canada (chapter 4). The results allow study of the year to year variations of the statistics of interest and will be of help in planning radio systems across Canada.

2. ATTENUATION BY RADAR

2.1 Introduction

The purpose of this work has been to obtain attenuation statistics for the Montreal region. In order to design a radio system it is desirable to know the probability of occurrence of attenuation events for one link down to a very low fraction of time (typically 10^{-8} of one year). For the Montreal region, one microwave link operating for a one year period provides a sample of sufficient size to contain events with a typical probability of about 10^{-6}. In a first approximation it would be necessary to operate some 100 links a year to reach the desired probability level, and this is just for one frequency and one hop length. It is obvious that this approach is not practical or economical. As an alternative, the information requested can be obtained empirically from several years of raingauge records (chapter 3) or from radar data. A radar can cover a large geographical region, thus providing a large number of paths over which attenuation events can be calculated. In this work this approach has been carried out, and attenuation statistics have been evaluated at 11.2, 12.7, 18.7 GHz. These statistics are for single links of various length, for pairs of parallel links with various separation distances and for a pair of links on the same route. With the method employed no information about the duration of the events is obtained, although this information, from the raingauge data, is given in chapter 3. Radar

simulation of attenuation has been used and studied by various authors (1,2,3,). There are two major problems that arise in this kind of approach: calibration of the radar and evaluation of absolute probabilities. They will be discussed in 2.3 and 2.4.

The data used in this study have been provided by the McGill Weather Radar and they cover the summer months of 1971. A brief description of the radar follows.

2.2 The McGill Weather Radar

During 1971 the main features of the radar were:

Frequency 2,880 MHz

Antenna Diameter 30-foot paraboloid (θ, $\phi = 0.8^{\circ}$)

Peak Power 2 MW

Pulse Repetition Frequency 60 Hz

Pulse length 0.3 μ sec (pulse compressing a 4 μ sec pulse with a factor 13)

Sensitivity - 104 dBm (equivalent to a rainfall rate of 0.2 mm/hr at 200 km)

Dynamic Range 80 dB.

Every 5 minutes the radar scans a hemisphere with a radius of 200 km. The scanning consists of successive azimuth rotations at different elevation angles from 0.5° to 33°. Each rotation is completed in 10 seconds. The measured reflectivity is stored on 35 mm films with 5 dB thresholds. Use is made of the range resolution of 50 meters in combining the data from several contiguous contributing volumes (5 at the closest range of 25 km and 80 at the furthest range of 200 km) and then peak detecting in order to reduce random-phase fluctuations (4,5,6,7).

The data format, AZLOR, is on rectangular coordinates, azimuth (600 values) on abscissa and logarithm of range on ordinate (200 values going from 25 to 200 km) (8).

Although this radar system has not been designed for attenuation studies, it is very adequate for the purpose and some of its features are very helpful in this respect.

The AZLOR data format, although it distorts shapes and does not conserve areas, is very rational and is well suited for the attenuation simulation carried on by computer. The main advantage over PPI is that the data are relative to square areas so that links can be simulated in radial and tangential direction easily and promptly.

The antenna program limits the sampling time to 5 minutes, when one is interested in a simulation over a place as close to the ground as possible, but offers the possibility of using a plane at higher elevation in the frequent case when the weather at lower elevation is masked by ground clutter, thus increasing substantially the sample size. This procedure must be applied with some caution in relation to the altitude of the echo, possible presence of bright band and generally altitude of the freezing level, to avoid a contamination of the data with precipitation other than rain for which attenuation properties are not yet well known.

2.3 Data collection and analysis

The 1971 summer data have been used to calculate attenuation statistics. For this purpose, out of the elevation cycles of the antenna, one azimuth scan was chosen with as low an elevation angle as possible in order to consider echoes below freezing level but high enough to avoid ground clutter effects. Except for a few cases the elevation angle used was 0.8° above the horizontal. In order to reduce the amount of data to be analyzed, a threshold was applied to the original reflectivity data such that only attenuation events over 10 dB were considered. For each scan the reflectivity data were read from the film and punched on cards. A program made corrections for peak reading as a function of the number of independent samples, which depends on range. The program then transformed the data from reflectivity to attenuation using the following relations:

$$\begin{aligned} Y(\mathrm{db/mi}) &= .0003795\ Z^{.775}(\mathrm{mm}^6/\mathrm{m}^3) && @\ 11.2\ \mathrm{GHz} \\ Y &= .0006431\ Z^{.750} && @\ 12.7\ \mathrm{GHz} \\ Y &= .00258\ Z^{.6875} && @\ 18.7\ \mathrm{GHz} \end{aligned} \tag{2.3.1}$$

The data were integrated over a dense grid of paths of various lengths and separation distances. The attenuation events were weighted in function of range because of the logarithmic distribution in range and then they were collected in histograms.

The network was composed of parallel and perpendicular links directed along and across range. The network of links did not have a fixed geographical location but it was simply superimposed on a patch of weather so that the maximum possible number of attenuation events was observed.

In this way the possibility of obtaining absolute probabilities is apparently lost; but this shouldn't be cause of grief because this possibility has been lost already for more helpless reasons than inadequate way of processing the data. In fact the radar wasn't working all the time, for various reasons: power failures, equipment failures, maintenance requirements, among which one in particular is annoying, i.e. the compulsion technicians have to run calibration patterns in the middle of the most interesting convective activity and then to run them again after a short time. Over the whole summer, the usable data for this analysis covered six different days for a total of 22 hours and 20 minutes, which is a small part of the whole summer.

One must bear in mind that the data collected were subject to the condition that they could generate attenuation events of at least 10 db. In this way not only a large portion of data for a given day were neglected but also whole days were not considered, so that the present data are representative of a period of time much larger than the six days over which they were collected. Unfortunately it is not possible to establish exactly the representativeness of the data because not enough is known about the weather when the radar wasn't in operation for the reasons above. Further, these reasons are not independent of the weather, in the case of power failures, thus complicating the problem further. In this work it has been assumed that the data are representative of the whole summer, although, a distinct possibility exists that significant data have been missed.

The various histograms of attenuation events can be interpreted as conditional distribution functions with the condition that the probability of the 10 dB event is given. They were integrated to give probabilities and normalized in such a way that the probability of the 10 dB event was unity. One example is given in fig. 2 for a length of 5 miles and at 11.2 GHz.

This was done for all lengths and all frequencies. To obtain absolute probabilities it is enough to estimate the probability of the 10 dB events and then to scale the probabilities for higher attenuation values accordingly.

As exposed in chapter 3, the estimate of the probability of the 10 dBz events can be obtained from raingauge records, thus allowing construction of absolute probability curves for all attenuation events. The actual results are presented in paragraphs 2.5 and 2.6.

2.4 Radar Calibration

The radar equation for weather radar with STC (sensitivity time control) can be written as:

$$(Z)_{dB} = C + (\overline{P}_r)_{dB} \qquad (2.4.1)$$

where Z is the reflectivity factor, $\overline{P}_r$ is the average received power and C is the calibration constant which includes the characteristics of the radar and the dielectric constant of the precipitation. C changes in time and has been determined daily following the procedure described by Smith (9). The radar data have then been used to calculate attenuation statistics for 5 mile links at 11.2 GHz and these have been compared with the one obtained by a real 5 mile link operating at Ormstown within radar range (10), fig. 2. The probability curves are normalized to 1 for 10 dB of attenuation and are obtained using different values of C in steps of 0.5 dB in order to obtain the best fit between the calculated and the observed statistics (dotted line). It is apparent that the computed statistics are very sensitive to the radar calibration. The probability of exceeding 30 dB changes by a factor 10 for only a 2 dB variation in the constant C. This effect is influenced by hop length and frequency and would be different if the curves were more logically normalized to 0 dB but this example at least gives an idea of the order of magnitude. 2 dB is about the accuracy one can reasonably expect from a careful electrical calibration of the radar. The importance of a calibration "ad hoc" is then apparent, that is a calibration based on the fit of the attenuation statistics obtained from a large sample of data. In this case the discrepancy between the "electrical calibration constant" and the "attenuation calibration constant" was about 4 dB which compares well with the value of 3.5 found by I. Strickland in Ottawa for 1970 data (2), following a similar method.

2.5 Single link attenuation probabilities

Following the method outlined in 2.3 and 2.4 attenuation statistics were obtained from radar observations in the summer of 1970.

Fig. 3 shows the probability that a given attenuation is exceeded at 11.2 GHz for various link lengths. For comparison fig. 3 shows the probability curve obtained from the real link (dotted) and the probability curve obtained for 5 mile links from 10 years of raingauge records normalized to the same probability for 10 dB (dashed).

It is possible to observe some interesting features. The lowest fraction of time observed for the single link is $\sim 10^{-6}$; for 10 link years is $\sim 10^{-7}$; for about a total of 24 hours of radar data is $\sim 10^{-8}$. All the curves are exponential until a certain value of probability and then they follow a law of the type $\frac{e^{-x}}{x}$. The single link is exponential until $\sim 3.10^{-5}$, the 10 years until $\sim 3.10^{-6}$ and the radar until $\sim 3.10^{-7}$. It appears that increasing the sample size increases proportionally the range of probability over which the process observed can be considered exponential. This suggests that the process is exponential and that it is our method of observation that introduces deviations from the exponential form.

Figs. 4 and 5 show the same statistics for 12.7 and 18.7 GHz. The hop length dependence is shown more explicitly in figs. 6,7,8, where the probability of a given attenuation is plotted versus hop length at the three frequencies. In fig. 6 the statistics from 10 years of raingauge records are plotted for comparison (dotted lines). The fit is forced on the 10 dB level.

2.6 Joint probabilities

For the design of twin route radio systems the knowledge of joint probabilities of parallel links is required.

The knowledge of joint probabilities of adjacent links on the same route is required if a too conservative design is to be avoided (11). Both these probabilities have been evaluated from the radar data. Figs.9, 10,11,12,13,14, show joint probabilities for parallel links at 11.2 GHz, for values of hop length of 2.5, 5, 7.5, 10, 12.5 and 15 miles versus separation distances. Figs.15, 16,17,18,19,20 are analogous to the previous one except at 12.7. Finally, figs.21,22,23 are at 18.7 GHz for hop length of 2.5, 5, 7.5 miles. As expected the joint probabilities approach the probabilities of single links when the separation distance approaches zero.

Conditional joint probabilities for links on the same route are given for adjacent links and links separated by a link length. It is preferred to use conditional probabilities instead of absolute joint probabilities because their use is more direct in the design of the communication system.

Figs. 24,25 show these statistics at 11.2 GHz, figs. 26,27 at 12.7 and figs. 28,29 at 18.7 GHz.

2.7 Accuracy of the results

There are many causes for errors in this approach. They correspond to the various steps necessary to arrive at the final results which consist of an estimation of the time that a given attenuation is exceeded. For this, measurements of reflectivity are made. The errors associated with these measurements depend on various factors, some of them controllable, some not. Random phase fluctuations are a first source of uncertainty which can be reduced increasing the number of independent samples (Smith, Marshall, Hitschfeld) (4,6). Reflectivity gradients also introduce uncertainties (Rogers) (7). Finally the reflectivity is stored in thresholds, in our case 5 dB, and this also introduces errors (Marshall) (5). Further, the McGill radar makes use of pulse compression and this introduces other uncertainties because of the time-side-lobes associated with this technique. The reflectivity values stored on film are then manually transferred to computer cards, thus introducing new errors, although the careful check employed limited this to a minimum. The simulation of attenuation introduces more errors because the exact length of the links could be obtained only in particular cases. The tolerance on length has been $\pm$ 10%.

The effect of all these factors is difficult to estimate. For this reason no clear statement on the accuracy of the method is available, although comparison of the results with the results of other independent approaches can be carried on. The statistics obtained with this approach compare very well with the ones obtained by a real link and by the raingauge method, figs. 3 and 6. From these comparisons it appears that the accuracy of the method is at least satisfactory because it produces estimates of attenuation probabilities that agree with estimates obtained independently.

2.8 Conclusions

Radar provides a powerful tool to evaluate attenuation statistics for microwave links. The main advantage over other methods is the enormous sample size of attenuation events that it is possible to collect in a few days. Of the six days considered here, two, 27 July and 10 August, contributed to most of the events. The reason is that one day of convective activity over a region of 200 km radius offers a full range of variability in rainfall rate and in precipitation patterns.

The sample size depends on the sampling time of the data and on the areal coverage of the radar. With the present antenna program of the radar the minimum

sampling time is 5 minutes. It was observed on a section of the data that sampling every 10 minutes did not affect the results so that it was possible to reduce the data analysis by a factor two. It was also found that sampling every 20 minutes affects the results. This obviously depends on the area and this problem will be studied in detail.

Disadvantages of a radar approach are, among others:

- great sensitivity to calibration, which imposes the auxiliary use of a microwave link or of a raingauge.
- practical impossibility of calculating, with the radar alone, absolute probabilities.

Furthermore, year to year variations in the statistics obviously cannot be extracted from a few days of radar data, but they can be evaluated by raingauge records or directly by microwave link data.

The joint probabilities presented here contain useful information about the spatial structure of precipitation patterns. At 18.7 GHz rainfall rate and specific attenuation are almost proportional, so that a value of attenuation is proportional to the amount of rain accumulated along the same path or to the rain accumulated to a point in an interval of time equal to the time necessary for the precipitation pattern to travel a distance equal to the path length. This equivalence of space and time statistics of precipitation pattern is known as the Taylor hypothesis. Evidence of the validity of this hypothesis can be found in the measurements of autocorrelation functions of precipitation patterns by Zawadzki (12) and in the successful application of this hypothesis to the use of raingauge records for evaluating attenuation statistics (Chapter 3). From the joint probabilities of attenuation for parallel or adjacent links it is possible to evaluate the joint probabilities of accumulated precipitation for points separated by various distances and for the various periods of accumulation. This statistic is of interest in a variety of applications.

3. ATTENUATION BY RAINGAUGE IN MONTREAL

3.1 Introduction

Rain attenuation statistics can be estimated from raingauge records provided that the speed of translation of the precipitation patterns is known. This approach is quite appealing because suitable raingauge records are available from many locations in Canada and for a sufficient number of years. This study establishes a technique to evaluate attenuation statistics from the raingauge records. The technique is then applied to calculate statistics for six locations across Canada for a period of time of ten years so that year to year variability can be accounted for. Further, ten years of data provide an adequate sample size. In this chapter the results for Montreal are presented, the results for the other locations being presented in Chapter 4.

3.2 Technique. Description and testing

The method of employing raingauge records to generate attenuation statistics is based on the concept of "synthetic storm", first used in 1961 by Hamilton and Marshall (13) to calculate the effects of rain attenuation on data obtained by a weather radar operating at a wavelength of 3 cm. The present method is an application of the Hamilton and Marshall concept to the estimation of attenuation over a particular ground communication link.

As a storm or rainfall pattern moves over a raingauge, the measured rainfall rate varies with time. The variations arise from two effects, the advection of the spatial pattern of rain and changes that occur within the time required to pass over the raingauge. These effects are both present in raingauge records and are not separable without additional information about the structure and motion of the rain pattern. The Hamilton-Marshall "synthetic storm" is a description of the rain pattern in terms of rainfall rate as a function of distance along a line in the direction of storm motion. It is obtained from a raingauge record by converting the raw data of rainfall rate versus time into a function of distance by employing a storm translation velocity to transform time to distance. In the original Hamilton-Marshall approach, weather radar data on storm motion provided the velocity needed for the time-to-distance conversion. As will be demonstrated below, radar data may not be essential for establishing this velocity.

Since the synthetic storm is based on the assumption that all time changes ob-

served at a point on the ground arise from the advection of spatial variations, it will not give an exact description of the distribution of rain with distance. It may be, however, that statistical properties of a large number of synthetic storms are approximately the same as the corresponding statistical properties of real storms. This is the hypothesis tested in the present study, where the properties of interest are certain integrals of the rainfall rate over specified distances.

This hypothesis is also known as Taylor's hypothesis. Evidence of it's validity can be found not only in this work but also in Zawadzki (12).

The synthesized storms express rainfall rate R as a function of distance x. As the first step in this analysis, rainfall rate is converted to specific attenuation Y through the formula

$$Y = kR^{\alpha} \quad (\text{dB/mi}) \tag{3.2.1}$$

where k and α are empirical parameters depending on radio frequency. The attenuation over a distance L may be calculated by integrating Y(x) over an interval of length L:

$$A(x_o,L) = \int_{x_o}^{x_o+L} Y(x)dx \ . \tag{3.2.2}$$

The result of this integration will generally depend on the starting point x_o as well as the length of the interval. The variation of attenuation with time can then be simulated by changing x_o at a rate equal to the velocity of storm motion. In order to test the technique the measurements obtained from the BNR link in Ormstown (fig. 1) were used. Three raingauges were located along the link and they supplied the rainfall data.

Fig. 30 illustrates a particular synthetic storm in terms of both rainfall rate and specific attenuation, with the time-to-distance conversion indicated.

Attenuation was calculated as a function of time for this storm by use of (3.2.2), with L set at 5 mi and x_o changing at a rate of 14 mi/hr (as obtained by radar). Values of k and α were selected to correspond to 11.2 GHz. The result of this calculation is shown in Fig. 31 and compared with the actual attenuation observed on the link.

That the calculated and actual attenuations are quite different is not surprising. First, the calculated attenuation cannot account for any time variations occurring in the storm as it moves along. Secondly, the simulated attenuation record corresponds to a link that is parallel to the direction of storm motion. In this example (as in most of the actual cases) the storm had an appreciable component of motion across the Ormstown link. Fig. 31 also shows that the simulated attenuation has a smoother curve than the observed attenuation. This is associated with the fact that the raingauge records do not allow rainfall rate to be measured with a time resolution better than about 1 min. No attempt was made to calculate attenuation with a finer resolution.

The experiment has been carried on for the summers of 1971 and 1972 and statistics from the link and the gauges are compared in fig. 32.

In these comparisons a set of values of k and α has been chosen so that the best fit is obtained. The values of k and α are given in table I for the three frequencies of interest, and they compare well with the values given in the literature, (14).
In spite of the fact that an individual synthetic storm may not lead to an attenuation record that agrees with observations, fig. 32 indicates a good agreement provided that the sample size is sufficient. While it may have been expected that the method of calculating attenuation would lead to some systematic bias effect, since all the simulated links are in the direction parallel to storm motion, this does not appear to be the case. Moreover, the results here indicate that the 1 minute resolution of the raingauges is adequate, at least over paths as short as 5 miles.

3.3 Dependence on the parameters

Velocity. The translation velocity of the storm plays an essential role in this analysis. Radar provides the best estimate of this velocity. But because radar facilities are not as common as raingauges, an attempt has been made to estimate the translation velocity from conventional radiosonde data. It has been found that the 700 mb wind nearest in time is a good estimate of the velocity. 700 mb corresponds on average to 3 km above sea level and is often referred to as "steering level". Fig. 33 compares probabilities obtained using radar and 700 mb velocities. The soundings are from Maniwaki 120 miles away from the experimental location (fig. 1). This comparison is considered successful and it justifies the use of radiosonde velocities as estimates of the translation velocity of precipitation patterns -

k and α .

The probability of a given value of attenuation depends on the value of k and α . In this study no direct evaluations of k and α were available so that values were chosen in order to have the best fit between calculated and observed statistics. This is a circular argument. To increase the confidence in the results the sensitivity of the results on k and α has been determined. The probability that a given attenuation is exceeded can be considered exponential:

$$P(A) = P_o e^{-A/A_o} \qquad (3.3.1)$$

where P_o is a function of hop length and A_o is a function of frequency and hop length; A is dependent on k and α .

It is of interest $\frac{\Delta P}{P}$ in function of Δk and $\Delta\alpha$.

P_o doesn't depend on k and α because it is the percentage of time when it rains. Differentiating one obtains:

$$\frac{\Delta P}{P} = \frac{A}{A_o^2}\left(\Delta\alpha\,\frac{\partial A_o}{\partial\alpha} + \Delta k\,\frac{\partial A_o}{\partial k}\right) . \qquad (3.3.2)$$

Using a set of values of k and α one can determine $\frac{\partial A_o}{\partial k}$ and $\frac{\partial A_o}{\partial\alpha}$ so that:

$$\frac{\Delta P}{P} \simeq 35\,\frac{A}{A_o^2}\,(\Delta\alpha + 10\,\Delta k) \qquad 11.2\text{ GHz}$$

$$\frac{\Delta P}{P} \simeq 38\,\frac{A}{A_o^2}\,(\Delta\alpha + 7.3\,\Delta k) \qquad 12.7\text{ GHz}$$

$$\frac{\Delta P}{P} \simeq 65\,\frac{A}{A_o^2}\,(\Delta\alpha + 2.2\,\Delta k) \qquad 18.7\text{ GHz} .$$

3.4 Ten years statistics - single links

Using the technique described in 3.2, ten years of raingauge records for Montreal have been analyzed. The years go from 1961 to 1970 and each year goes from May to September.

Fig. 34 shows the probabilities obtained for 5 miles hop length at 11.2 GHz for the 10 different years. 1964 has a peculiar behavior: one storm is such that it extends the curve up to 74 dB. This is the record storm for Montreal with an intensity of 460 mm/hr. The return period of this event exceeds 100 years so that it cannot be included in averages over a ten year period. For this reason it has been disregarded in the analysis.

It is not clear to the author which is the best form of presenting statistics of events like the one in fig. 34. It has been decided to plot average probabilities over ten years for various hop lengths and frequencies (in this paragraph) and to describe year to year variability separately (3.8). An alternative approach is illustrated in fig. 35, where not only average probabilities are plotted but also probabilities corresponding to certain percentages of the population. The probabilities of a given attenuation in the various years are assumed to be random events normally distributed. Although this approach is limited here to one frequency and one link length it can be extended to other values using the data on year to year variability in 3.8.

Figs. 36,37,38 plot probabilities versus attenuation at 11.2, 12.7, 18.7 GHz; for hop lengths of 2.5, 5, 7.5, 10, 12.5, 15 miles. The curves are straight lines until a certain percentage of time ($\sim 3.10^{-6}$ of one year) so that the probabilities can be considered exponential until that probability level. Comparison with radar data for larger sample size (paragraph 2.5) suggests that this is an observation effect due to insufficient sample, so that the probabilities should be considered exponential all the way.

3.5 Joint probabilities

With the same technique described in 3.2 it it possible to calculate statistics of joint attenuation events for successive links, these statistics being of interest in the planning of radio systems. Statistics for adjacent links are plotted in figs. 39, 40,41 in the form of conditional probabilities, the condition being that a given attenuation is exceeded on one of the links. At 18.7 GHz the plots are limited to a length of 5 miles. Figs. 42,43,44 present the same statistics for links separated by a hop length.

3.6 Durations

Table II presents a comparison of the durations of the attenuation events in the 1971 Ormstown experiment. It appears that the link and the raingauges agree although the sample size is so small that it is impossible to assess the capability of the raingauge to reproduce the statistics of

durations experienced by the link. Nevertheless, it appears that the two sets of observations are consistent. Histograms of durations of fade are presented for various lengths at 11.2 GHz only in the tables III, IV, V, VI, VII, VIII. As an example, figs. 45 and 46 show the dependence on hop length and on attenuation level.

3.7 Frequency dependence

From the 10 years statistics presented in figs. 36,37,38 it is possible to obtain some information about frequency dependence of attenuation probabilities. In figs. 47,48, 49 attenuation of events with the same probability and hop length but different frequency are correlated so that the following empirical results are found:

$$A_{18.7} = 2.4\ A_{11.2} \qquad (3.7.1)$$

$$A_{18.7} = 1.9\ A_{12.7} \qquad (3.7.2)$$

$$A_{12.7} = 1.25\ A_{11.2} \qquad (3.7.3)$$

which relate the values of attenuation at two frequencies for the same length and probability.

From the above relations one can obtain:

$$\left(\frac{A_f}{A_{fo}}\right) = \left(\frac{f}{f_o}\right)^{1.72} \qquad (3.7.4)$$

which at least in the range 11 to 18 GHz allows one to calculate empirically the attenuations of an event at frequency f given the attenuation of the same event at f_o, the same event meaning the same link length and probability.

3.8 Year to year variability

As can be seen in fig. 34 there is a substantial variation in the probability of a given attenuation event across the years.

For any length and frequency the probability that a given attenuation is exceeded for a given year is very likely to be a Gaussian variate. X^2 tests for typical values cannot reject this hypothesis at any probability level but the number of samples is so small that the significance of the test is, at least, dubious.

These yearly variations have to be taken into account in the planning of radio systems and also in establishing the duration of experiments to collect attenuation statistics. These variations depend on frequency and link length in a complicated way. In fig. 50 the coefficient of variation of the probability of a given event is plotted as a function of hop length for discrete attenuation levels. The coefficient of variation is defined as follows:

$$\text{c.o.v.} = \frac{S}{\mu} \times 100$$

where S is the sample variance and μ is the sample mean, the variable being the probability of a given event.

4. ATTENUATION BY RAINGAUGE ACROSS CANADA

4.1 Introduction

For the purpose of obtaining some information about the geographical dependence of the attenuation statistics of interest, 5 more locations have been selected to carry on a study similar to the one carried on for Montreal. Fig. 51 shows these locations and the radiosonde stations whose upper air data were employed in the analysis. As in Montreal, 10 years of raingauge data were analyzed for each location covering the months from May to September for the decade from 1962 to 1971. The actual locations were chosen as corresponding to highly populated regions and with the intention of covering the possible routes of Canadian radio systems. The west coast and the Rocky Mountains were excluded because of the strong orographic character of the precipitation there.

The results of this study are certainly not conclusive or complete, leaving large parts of the country uncovered. In particular, the region between Halifax and Montreal needs further analysis as well as the region between Edmonton and Winnipeg. Nevertheless an overall pattern appears from the available data. There is a region containing Montreal, Toronto, Thunder Bay and Winnipeg where attenuation statistics are severe and particularly similar for the four locations. East of this region, maritime climate generates less severe statistics (Halifax), and westward (Edmonton) less severe statistics occur in correspondence to a continental climate. The boundaries of this region are not well defined at this stage of the analysis.

In carrying on this study a further hypothesis has to be introduced. That is that the 700 mb winds are representative of the precipitation patterns motion all over the country. This is largely arbitrary because this hypothesis has been tested only

in Montreal (fig. 33). Nevertheless this appears to be a reasonable hypothesis and certainly not a critical one; fig. 52 shows Winnipeg statistics calculated using radiosonde data from International Falls and Sault Ste. Marie. The curves are very close to each other thus insuring a certain reliability to the study. In the following paragraphs the statistics for the various locations are presented.

4.2 Halifax

Figs. 53,54,55 show probabilities versus attenuation at 11.2, 12.7, 18.7 GHz. Like for Montreal the probability that a given attenuation is exceeded decreases exponentially versus attenuation at least to a probability of about 3.10^{-6} of one year.

The joint probabilities (figs. 56, 57,58,59,60,61) are very small for every value of attenuation, length and frequency. This result has important consequences for the design of radio systems because attenuation events on consecutive links can then be considered independently.

Tables IX to XIV present histograms of duration at 11.2 GHz for various hop lengths. Fig. 62 shows the coefficient of variation across ten years. For the definition of these curves see paragraph 3.8. The curves in fig. 62 differ from the Montreal one, fig. 50, in the sense that the variability in Halifax is substantially larger, and the length dependence is different, suggesting smaller high rate rain cells than in Montreal.

4.3 Toronto

Figs. 63,64,65 show probabilities versus attenuation at 11.2, 12.7, 18.7 GHz. The curves are very close to those for Montreal although, as will be seen in paragraph 4.7, the precipitation statistics are different.

The joint probabilities (figs. 66, 67,68,69,70,71) suggest complicated interactions between cell size and hop lengths. They are generally higher than in Halifax and similar to those in Montreal. The values are such to make these statistics an important factor in the design of radio systems.

Histograms of duration at 11.2 GHz are given in the tables XV to XX in correspondence to various lengths.

The coefficients of variations are plotted in fig. 72 (for the definition see paragraph 3.8). It appears that the yearly variability is generally somehow higher than in Montreal and less than in Halifax.

4.4 Thunder Bay

As the name says, Thunder Bay is quite stormy at least for what concerns attenuation. Figs. 73,74,75 show probabilities versus attenuation at 11.2, 12.7, 16.7 GHz. These curves are very close to the ones for Montreal and Toronto. The joint probabilities (figs. 76,77,78,79,80,81) are close to the Montreal-Toronto ones for short lengths and somehow less for longer lengths suggesting smaller sizes of rain cells. Also in Thunder Bay the values of joint probabilities are such to make them relevant in the design of radio systems.

Histograms of duration are presented in Tables XXI to XXVI. The coefficients of variation are plotted in fig. 82 (for the definition see paragraph 3.8). Relative to the other locations the variability in Thunder Bay is higher than in Montreal, slightly higher than in Toronto and lower than in Halifax.

4.5 Winnipeg

Figs. 83,84,85 show probabilities versus attenuation at 11.2, 12.7, 18.7 GHz. Again these curves are very similar to those for Montreal. In calculating these curves some extreme events were discarded from the data.

The joint probabilities (figs. 86, 87,88,89,90,91) are very similar to those for Montreal.

Histograms of durations are presented in Tables XXVII to XXXII. The coefficients of variation are plotted in fig. 92 (for the definition see paragraph 3.8). Relative to other locations the variability in Winnipeg is higher except for Halifax.

4.6 Edmonton

A well established pattern of similarities in the attenuation statistics is encountered moving westward from Montreal. This pattern presents a marked discontinuity in Edmonton and whether this is the result of a gradual change or of an abrupt discontinuity somewhere between Winnipeg and Edmonton is not yet known. The available climatological data do not furnish an explanation of this problem and it will probably be necessary to analyze raingauge data for locations between Winnipeg and Edmonton.

Figs. 93,94 and 95 show probabilities versus attenuation at 11.2, 12.7 and 18.7 GHz. For any length and frequency the probability of exceeding a given attenuation is much less than in any other locality in

this study, thus allowing much longer hop lengths.

The joint probabilities (figs. 96, 97, 98, 99, 100 and 101) are so small that no advantage can be obtained by taking them into account for the design of radio systems. The behaviour of the single link and joint link statistics in Edmonton can be interpreted in terms of frequency of occurrence of given rain events and their size. Something in this line will be attempted in the next paragraph.

Histograms of durations at 11.2 GHz are given in Tables XXXIII to XXXVIII. The coefficients of variation are plotted in fig. 102 (for the definition see paragraph 3.8), they are generally higher than in the other locations but, of course, the smaller sample size of the events has to be taken into account in explaining this behaviour.

4.7 Comparisons

As stated in para. 4.1, the six locations considered can be, in many respects, distributed in three groups with different properties. Fig. 103 shows, the attenuation exceeded for a probability of 10^{-5} of one year in function of hop length for the six locations. It is apparent that Montreal, Toronto, Thunder Bay, Winnipeg behave very much in the same way, while Halifax and Edmonton have a different behaviour. A similar pattern could be observed for the joint probabilities although less clearly because these quantities are determined with a smaller sample size and thus with less statistical accuracy. The year to year variability doesn't follow a pattern as clear as the one for the probabilities, and a comparison between the locations must take into account the relative sample sizes. For these reasons some statistics of the precipitation processes in the various locations are presented here, having been obtained from the same raingauge records used for the attenuation studies.

Table XXXIX shows the number of precipitation events in ten years exceeding a given rainfall rate in the six locations, and Table XL shows the features of the population of the event sizes. It appears, for instance, that the behavior of Edmonton statistics is consistent with these data which show rarer and shorter events which corresponds to smaller probability of a given attenuation.

4.8 Planning a radio system across Canada

The result presented here so far can be used for the planning of a radio system across Canada, at least in a general sense. They are by no means sufficient for a practical design for which a more detailed coverage of the country would be needed. In a general sense the data presented here allow some considerations:

It appears that there is one large region, at least extending from Montreal to Winnipeg, where the probability of exceeding a given attenuation is almost uniform so that a uniform criterion of design is allowed. Inside this region year to year variability is larger in certain places than in others so that in order to have uniform performances some allowances have to be made in this respect. In this region the spatial structure of the precipitation pattern is such that joint events of sizeable attenuations are frequent enough to make it worth taking them into account for more economical planning.

Outside this region, both eastward and westward, the probabilities are lower thus making possible the use of longer hop lengths although this advantage is partially compensated by larger year to year variability and independency of events. The boundaries of the region are not known, so that it is impossible to evaluate accurately the cost of a system. For this further studies are necessary.

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8) __, G. Drufuca and I.I. Zawadzki, 1971. Attenuation statistics from weather radar observations. G-AP International Symp., Los Angeles 1971.

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11) Hogg, D.C., 1969: Statistics on attenuation of microwaves by intense rain. BSTJ.

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13) Hamilton, P.M., and J.S. Marshall, 1961. Weather-radar attenuation estimates from raingauge statistics. Stormy Weather Group Report MW-32, McGill University, Montreal.

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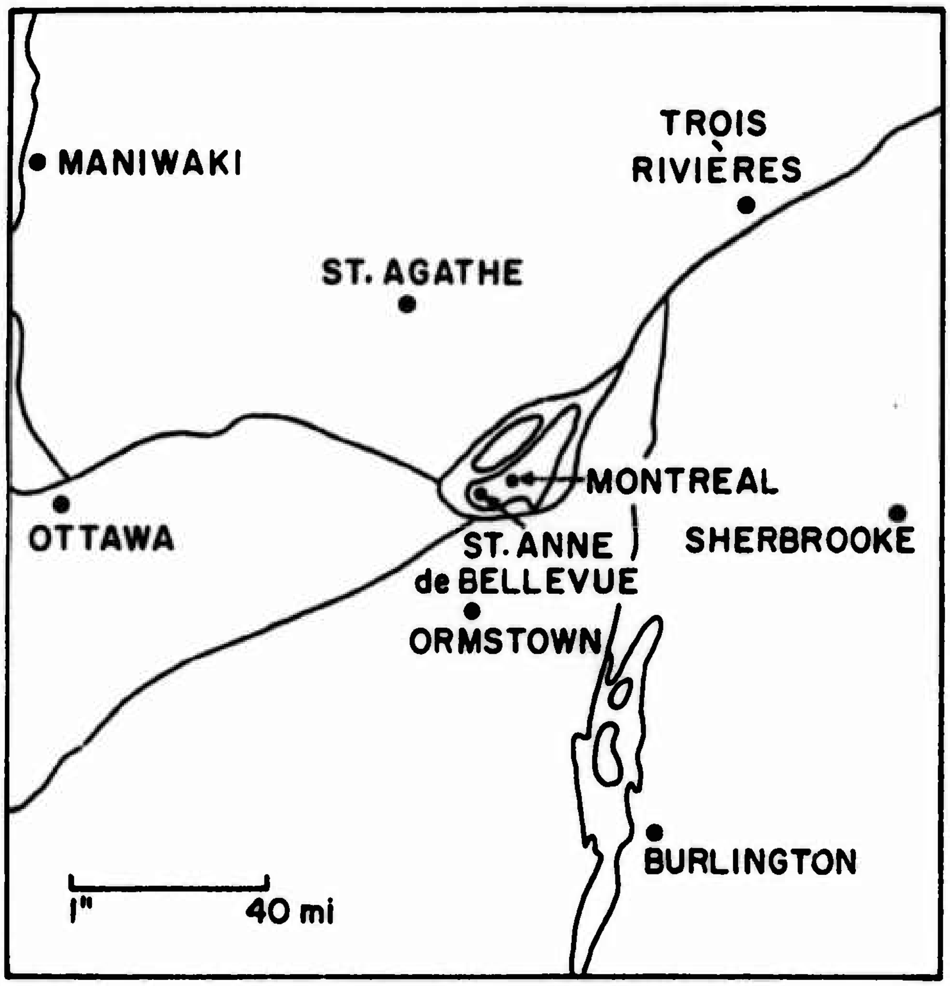


Fig. 1. The experimental link was located in Ormstown 20 miles south of Montreal.

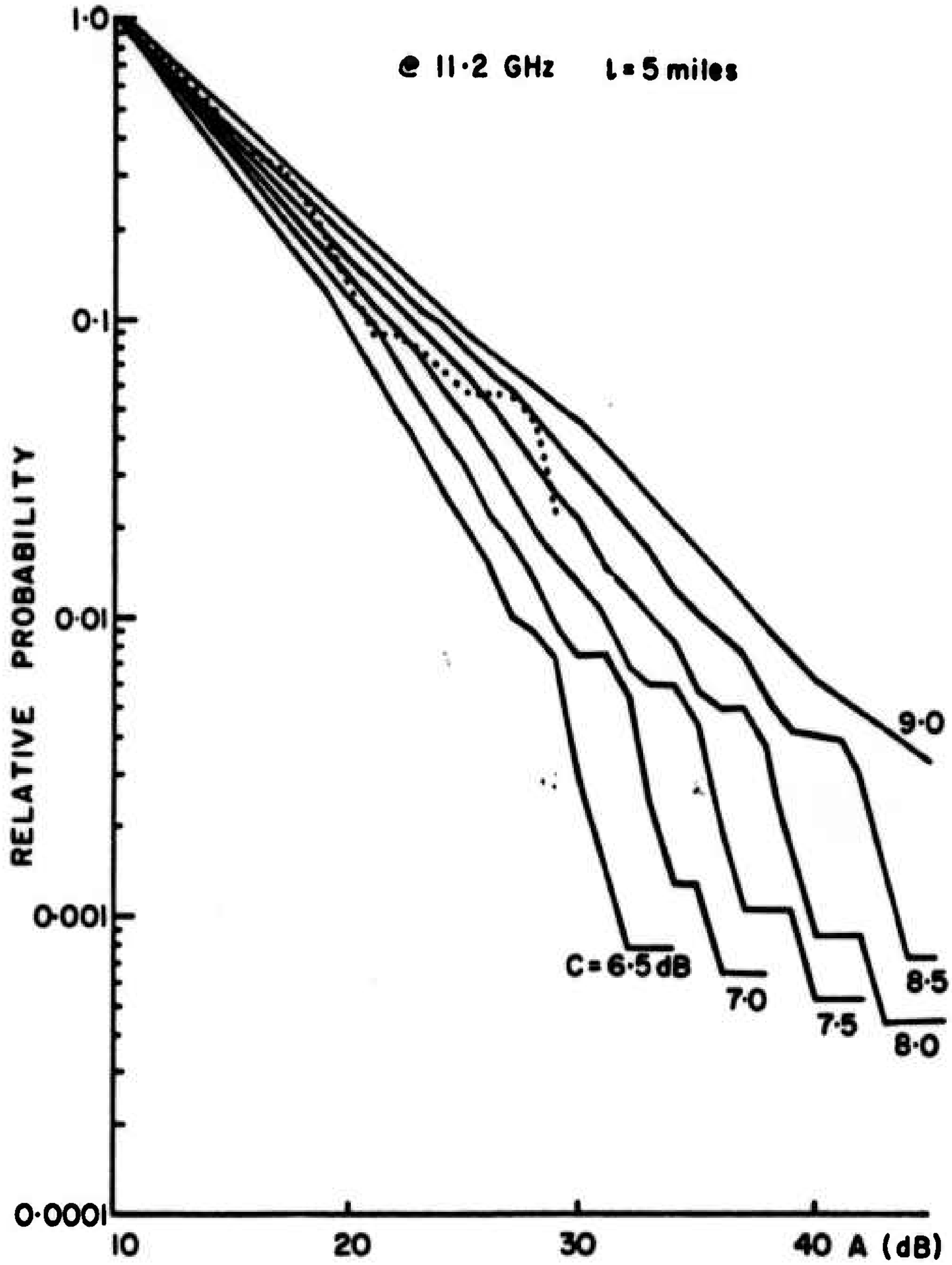
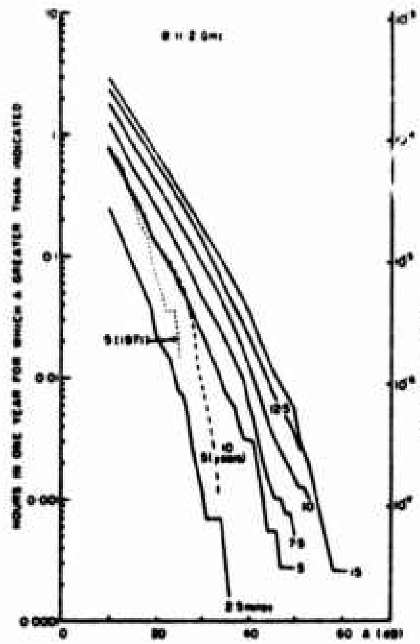
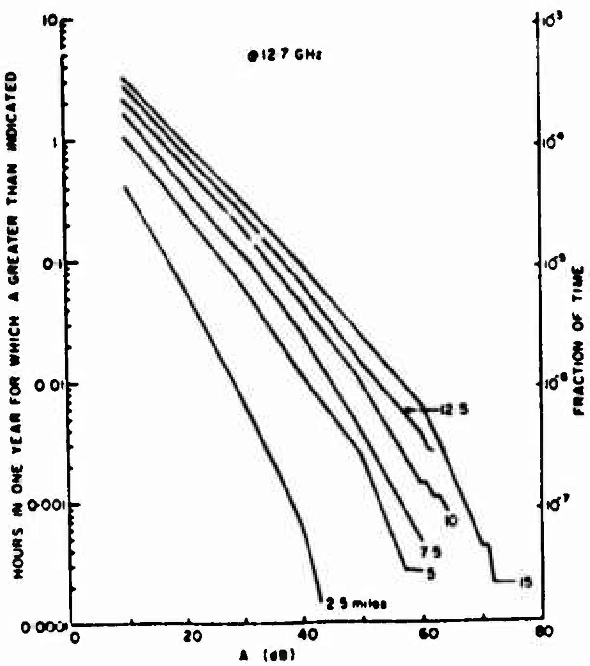
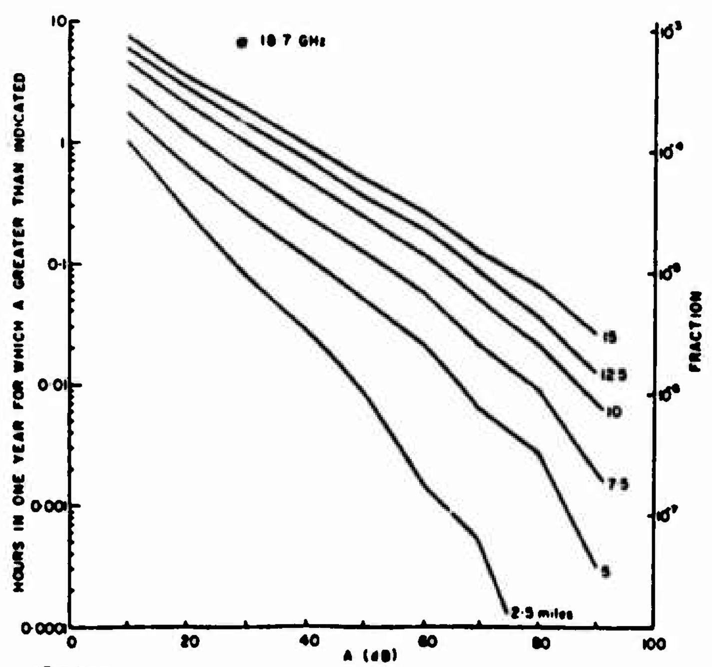


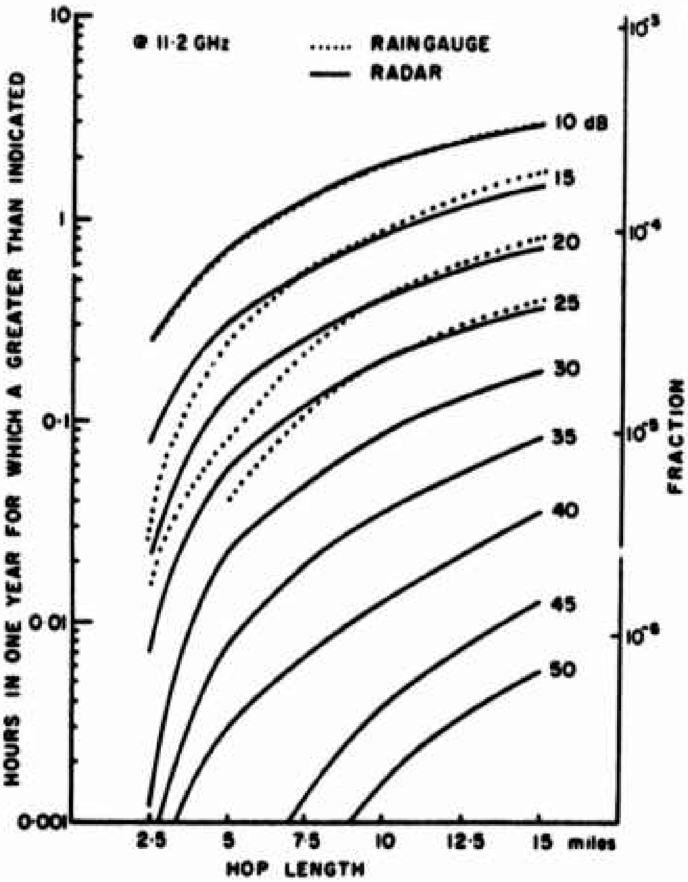
Fig. 2. Relative probabilities that a given attenuation is exceeded (continuous lines) as obtained for different values of the calibration constant (in a relative scale). The dotted curve is obtained from the experimental link. All curves are normalized to 1 for 10 dB of attenuation.



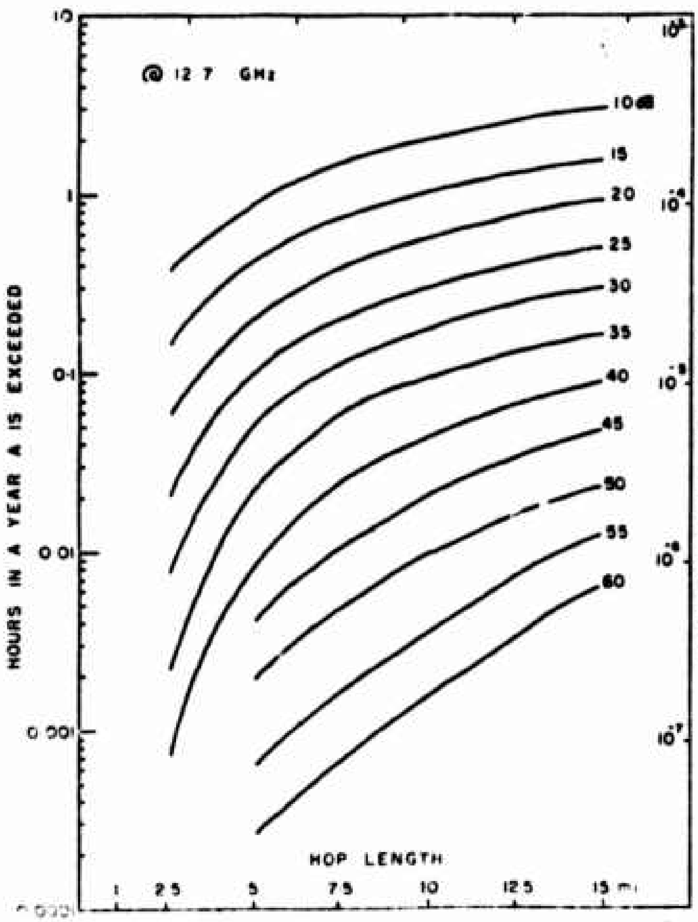
Figs. 3,4,5 (Left; Below Left; Below Right). Probability that a given attenuation is exceeded at 11.2, 12.7, and 18.7 GHz for various link lengths. In Fig. 3 the dotted curve is from the 1971 experiment in Ormstown. The dashed curve is obtained from 10 years of raingauge records and has been normalized to the same probability for 10 dB.

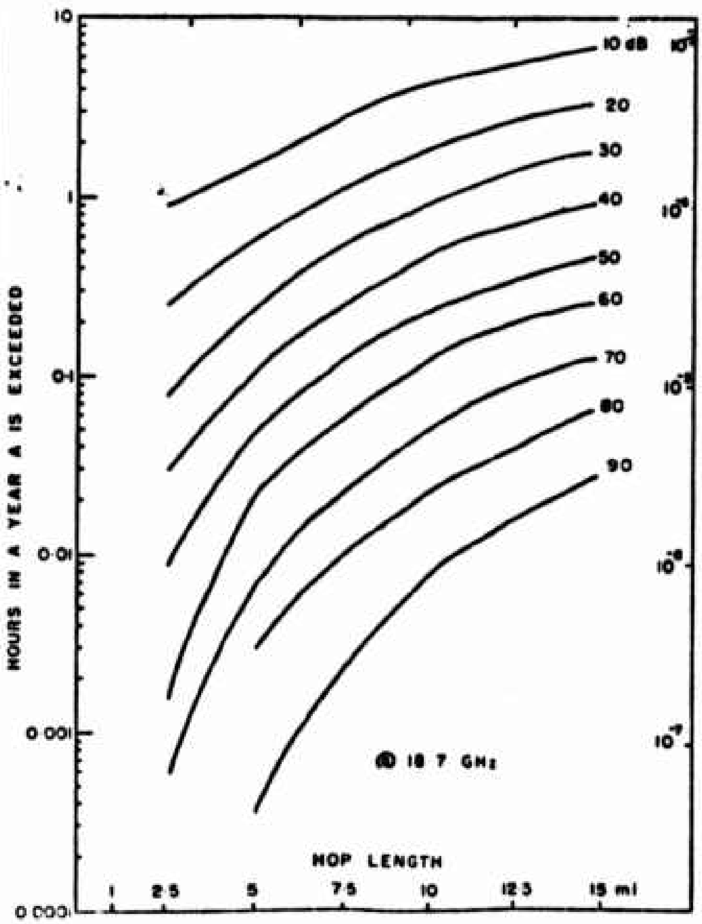


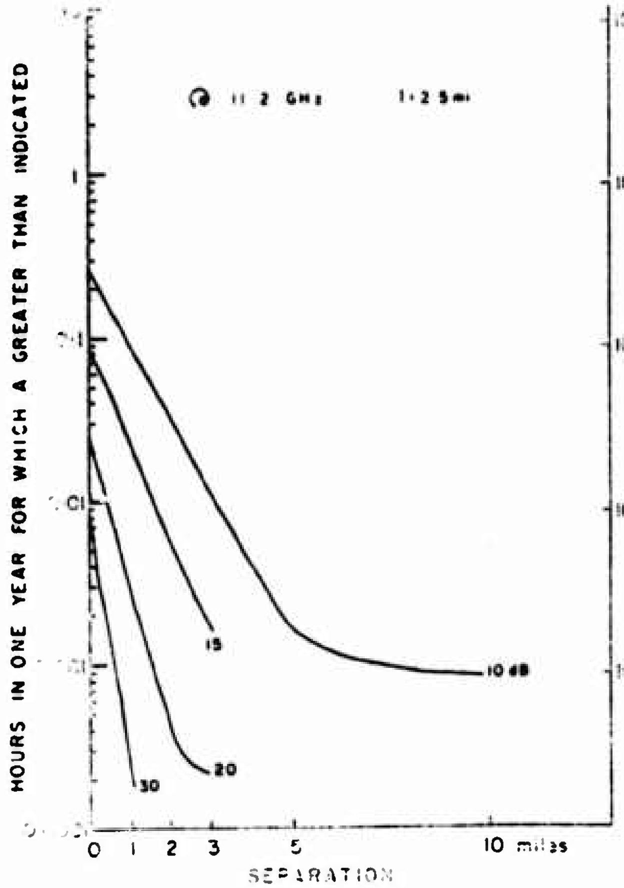


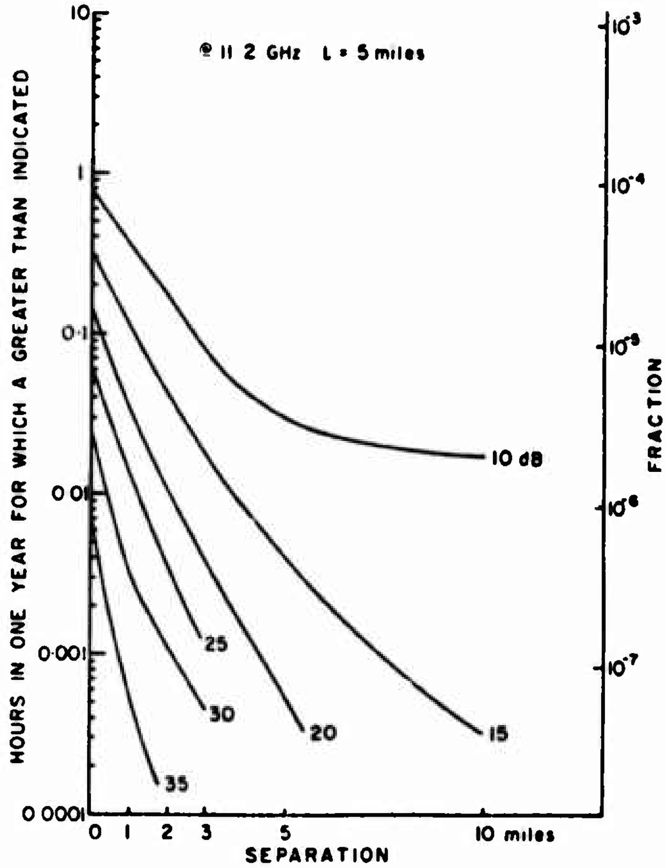


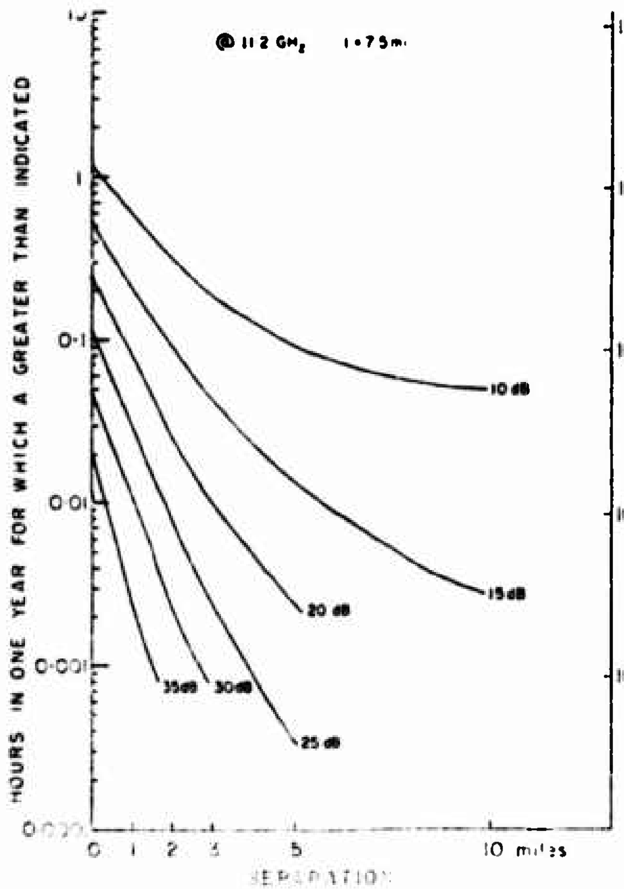
Figs. 6,7,8 (Left; Below Left; Below Right). Probability that a given attenuation is exceeded at 11.2, 12.7, and 18.7 GHz versus hop length. In Fig. 6 the dotted lines are from 10 years of raingauge records. A fit has been forced at the 10 dB level. The scale on the left is fraction of one year.

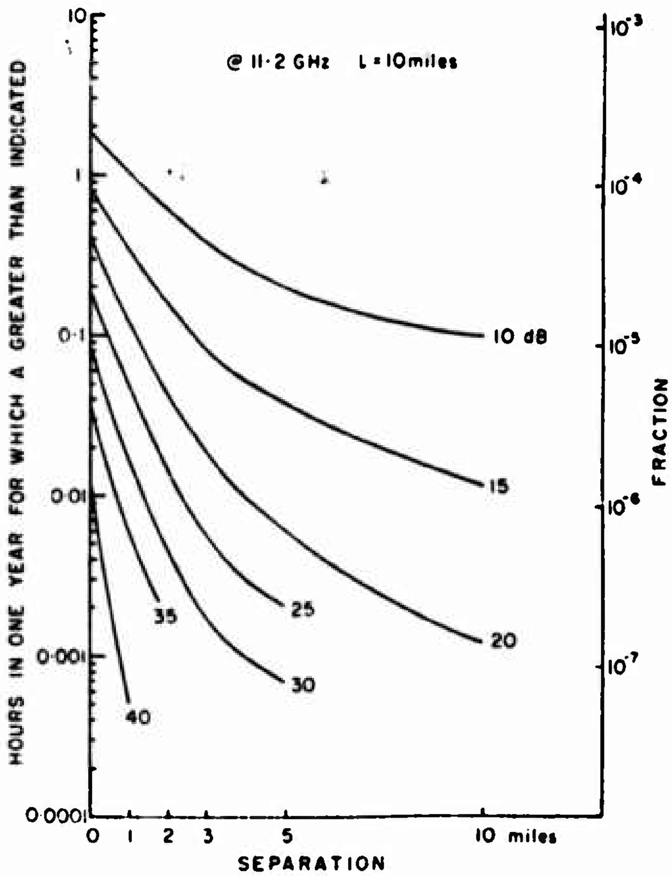


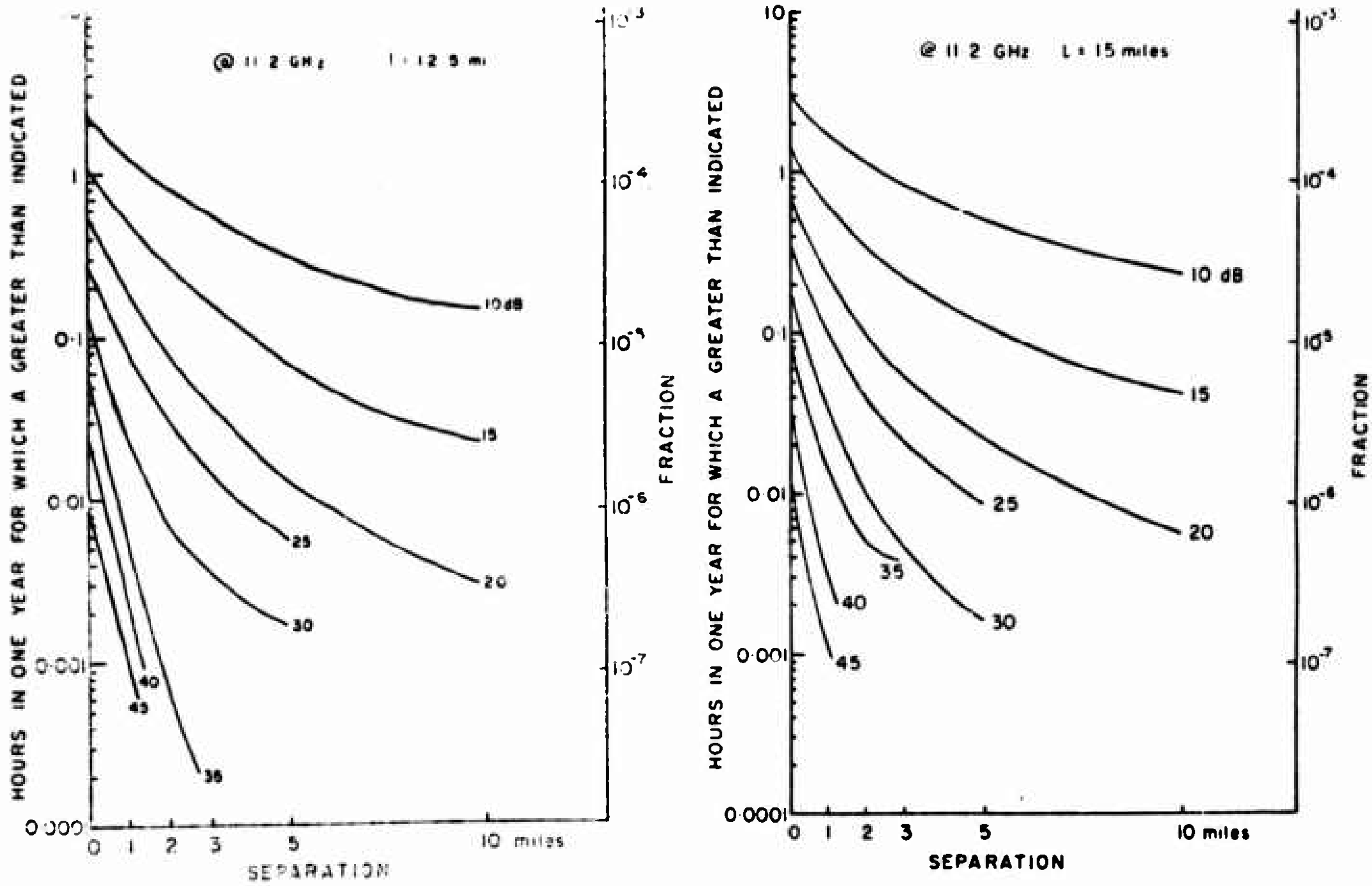



@ 11 2 GHz l = 2.5 mi
HOURS IN ONE YEAR FOR WHICH A GREATER THAN INDICATED
FRACTION
1
0.1
0.01
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
15
10 dB
20
30
0
1
2
3
5
10 miles
SEPARATION

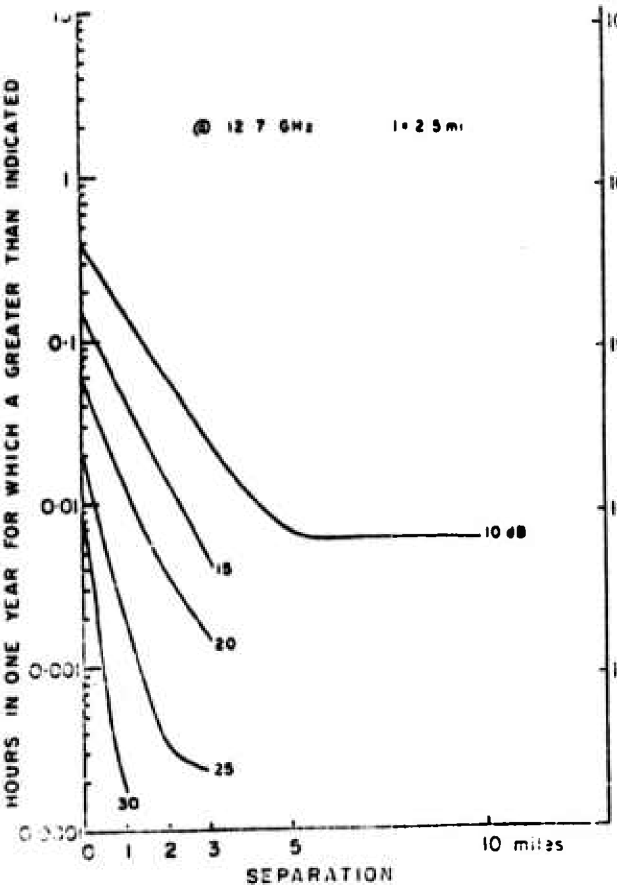

@ 11 2 GHz L = 5 miles
HOURS IN ONE YEAR FOR WHICH A GREATER THAN INDICATED
FRACTION
10
1
0.1
0.01
0.001
0.0001
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10 dB
25
30
20
15
35
0
1
2
3
5
10 miles
SEPARATION

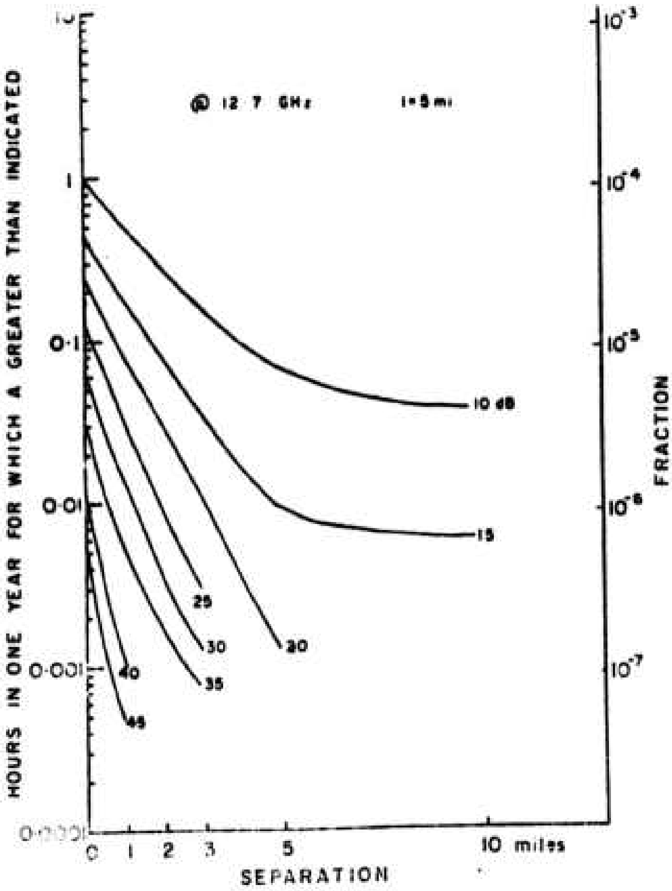

@ 11 2 GHz l = 7.5 mi
HOURS IN ONE YEAR FOR WHICH A GREATER THAN INDICATED
FRACTION
1
0.1
0.01
0.001
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10 dB
15 dB
20 dB
35 dB
30 dB
25 dB
0
1
2
3
5
10 miles
SEPARATION

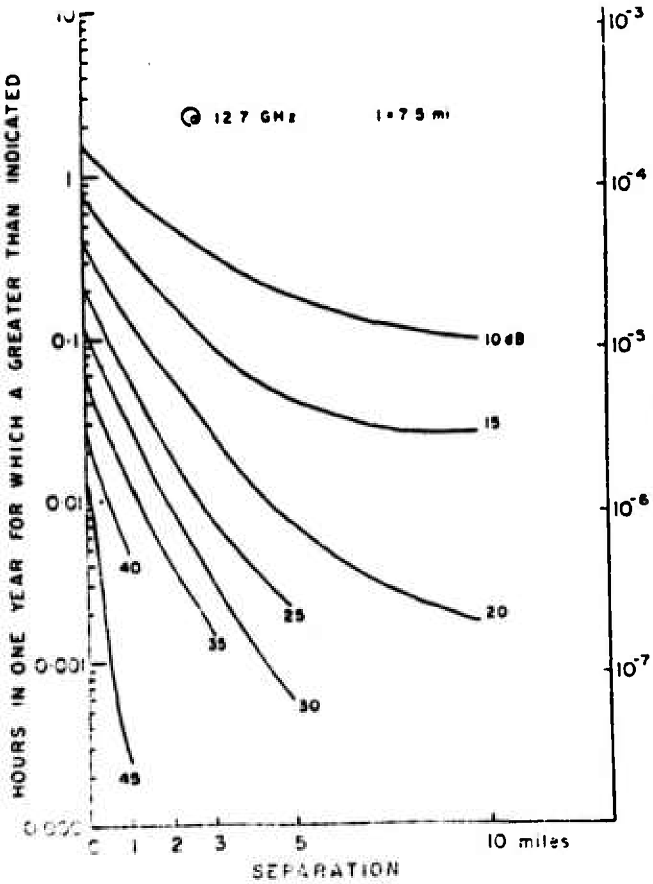

@ 11·2 GHz L = 10 miles
HOURS IN ONE YEAR FOR WHICH A GREATER THAN INDICATED
FRACTION
10
1
0.1
0.01
0.001
0.0001
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10 dB
15
25
20
35
30
40
0
1
2
3
5
10 miles
SEPARATION

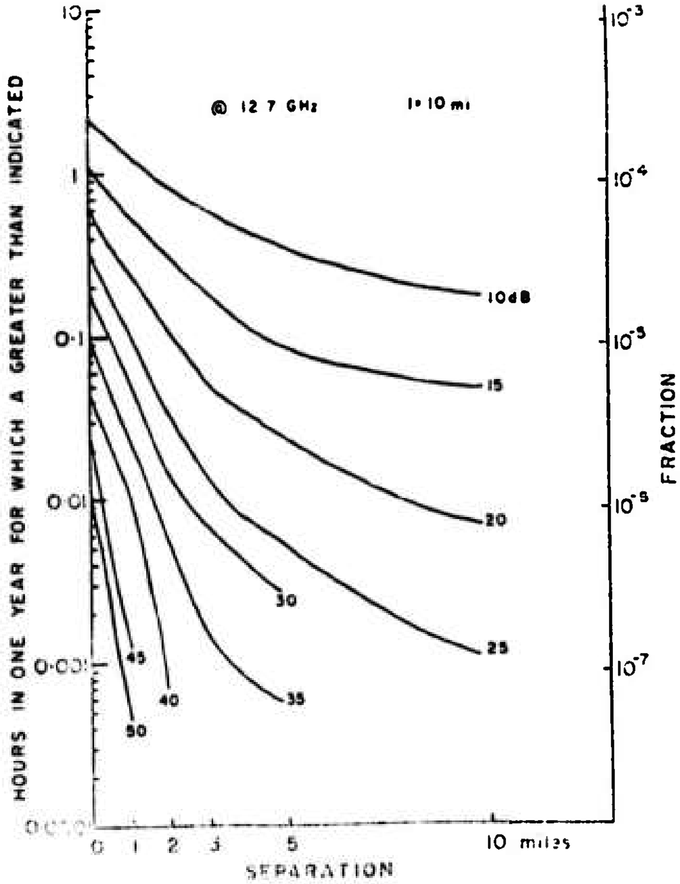


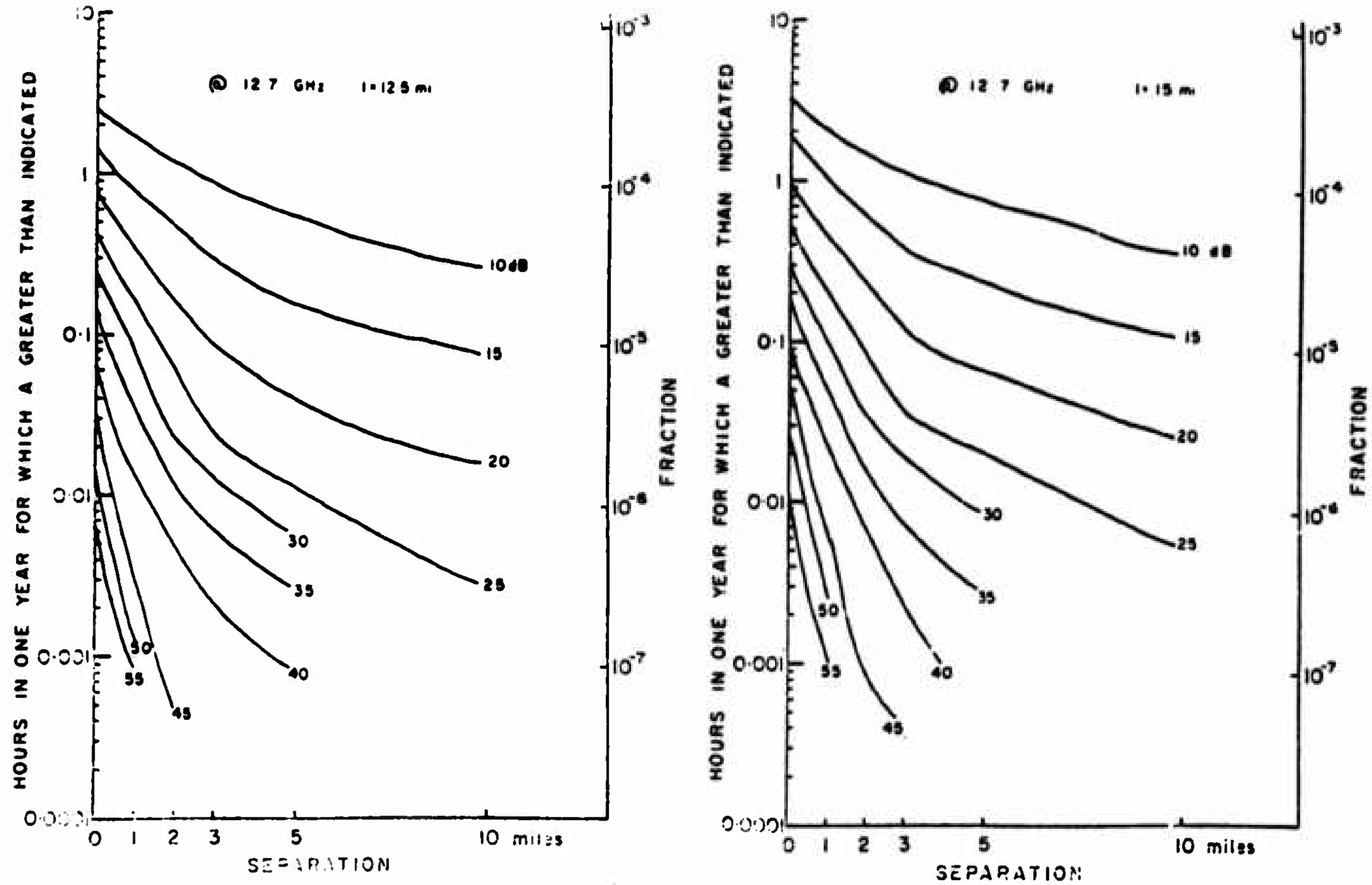
Figs. 9 to 14. Probability that a given attenuation is jointly exceeded on parallel links at 11.2 GHz versus separation distance for various hop lengths.


@ 12.7 GHz
l = 2.5 mi
HOURS IN ONE YEAR FOR WHICH A GREATER THAN INDICATED
FRACTION
10 dB
15
20
25
30
SEPARATION
10 miles


@ 12.7 GHz
l = 5 mi
HOURS IN ONE YEAR FOR WHICH A GREATER THAN INDICATED
FRACTION
10 dB
15
20
25
30
35
40
45
SEPARATION
10 miles

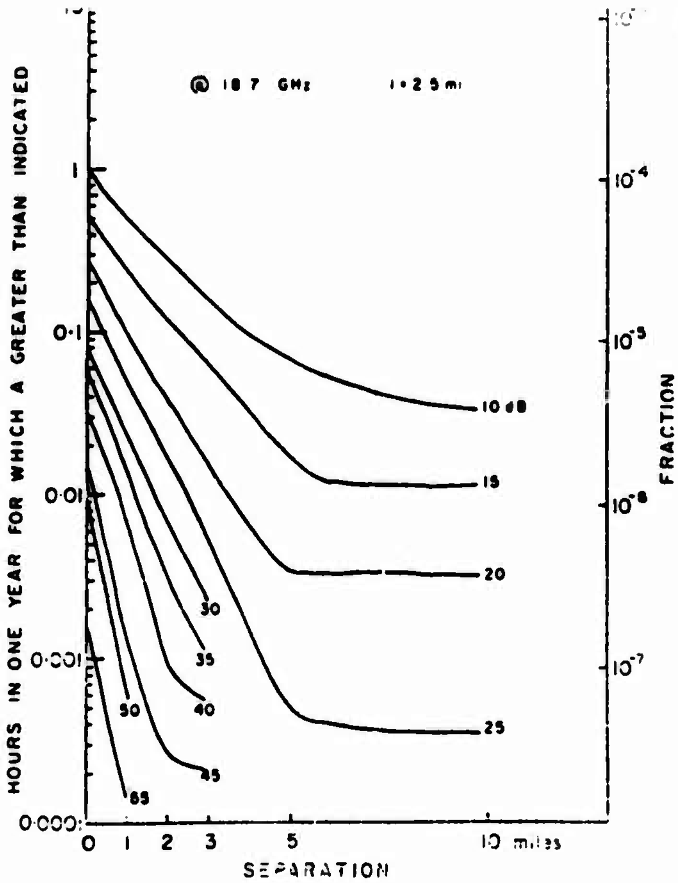

@ 12.7 GHz
l = 7.5 mi
HOURS IN ONE YEAR FOR WHICH A GREATER THAN INDICATED
FRACTION
10 dB
15
20
25
30
35
40
45
SEPARATION
10 miles

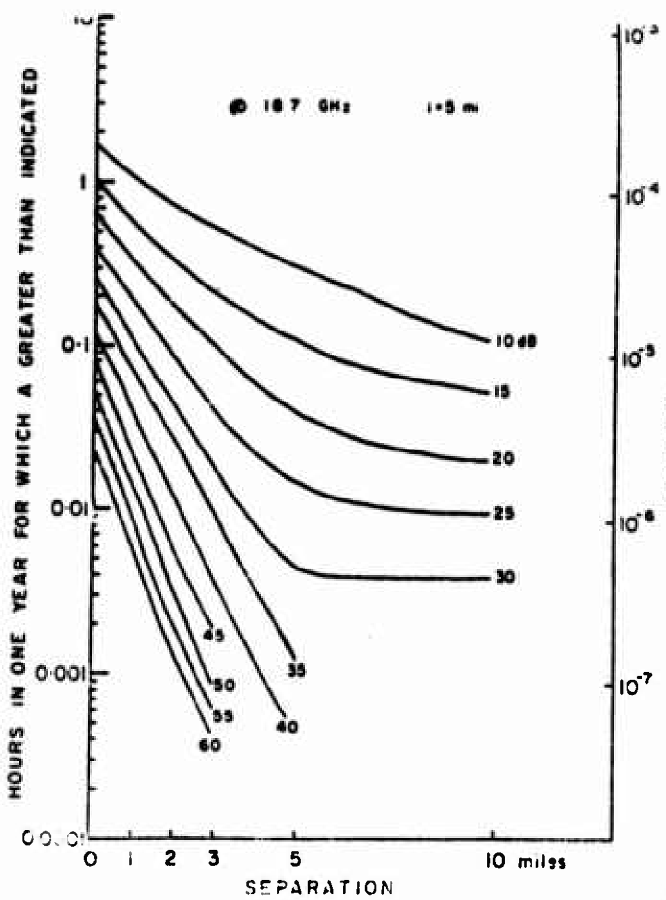

@ 12.7 GHz
l = 10 mi
HOURS IN ONE YEAR FOR WHICH A GREATER THAN INDICATED
FRACTION
10 dB
15
20
25
30
35
40
45
50
SEPARATION
10 miles

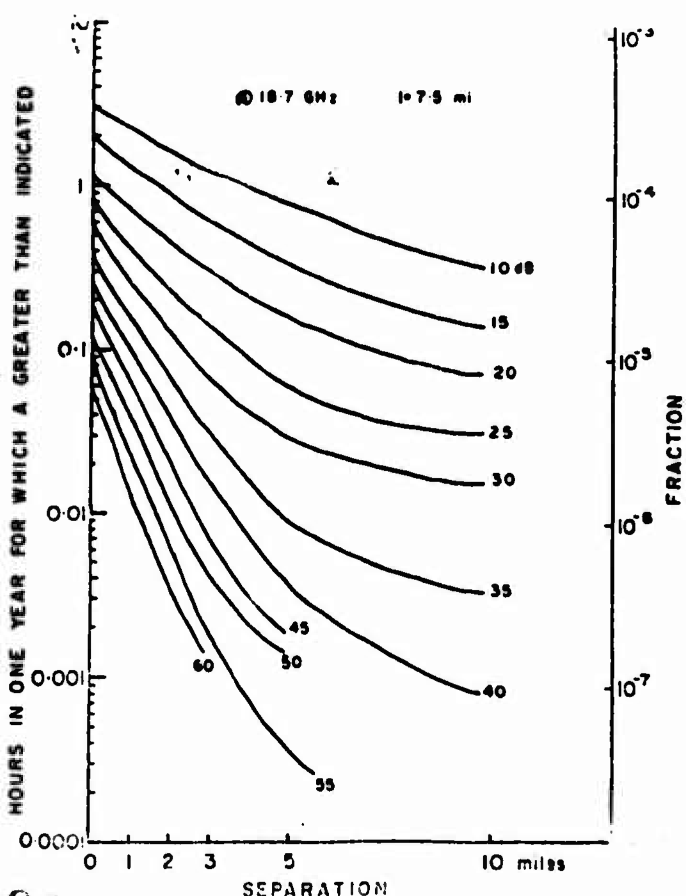


Figs. 15 to 20. Probability that a given attenuation is jointly exceeded on parallel links at 12.7 GHz versus separation distance for various hop lengths.

Figs. 21,22,23 (Left; Below Left; Below Right). Probability that a given attenuation is jointly exceeded on parallel links at 18.7 GHz versus separation distance for various hop lengths.







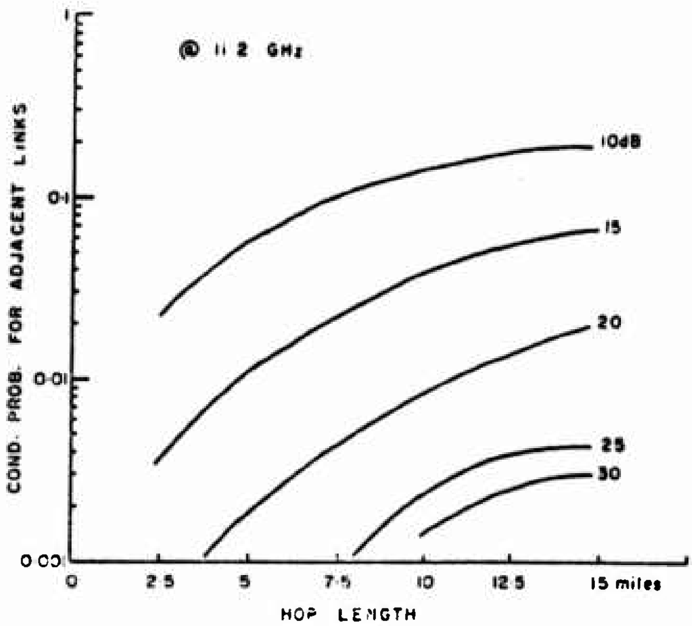


Fig. 24. Conditional probability that a given attenuation is exceeded jointly on consecutive links versus hop length at 11.2 GHz.

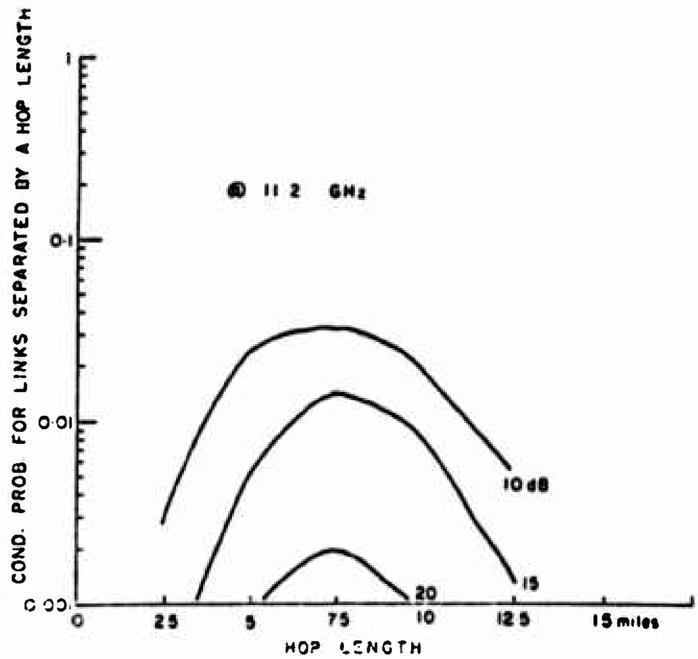


Fig. 25. Conditional probability that a given attenuation is exceeded jointly on links separated by a hop length versus hop length at 11.2 GHz.

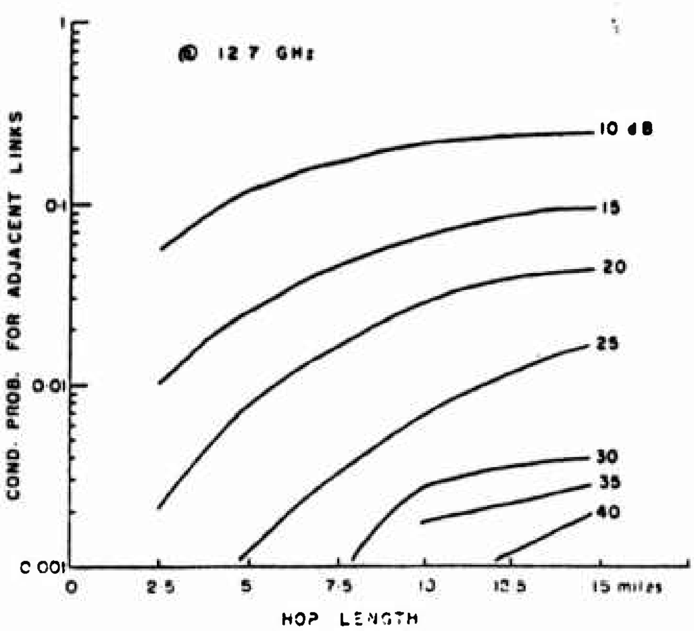


Fig. 26. Conditional probability that a given attenuation is exceeded jointly on consecutive links versus hop length at 12.7 GHz.

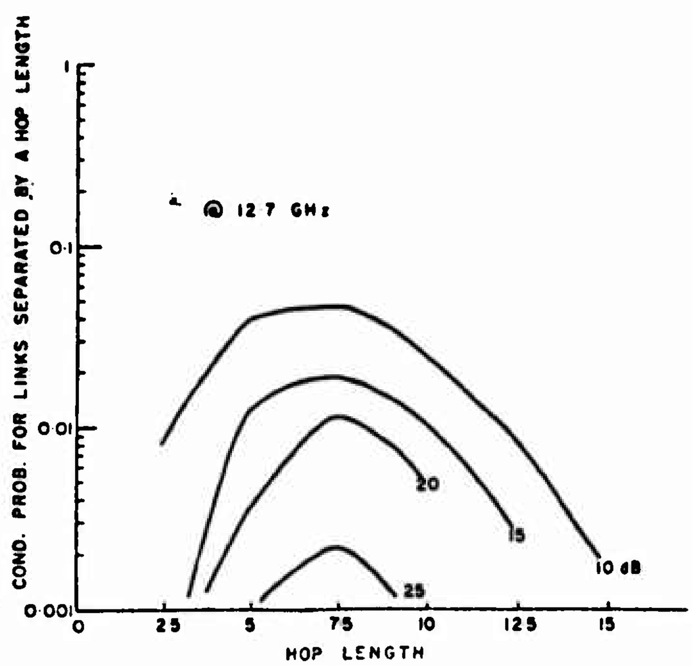


Fig. 27. Conditional probability that a given attenuation is exceeded jointly on links separated by a hop length versus hop length at 12.7 GHz.

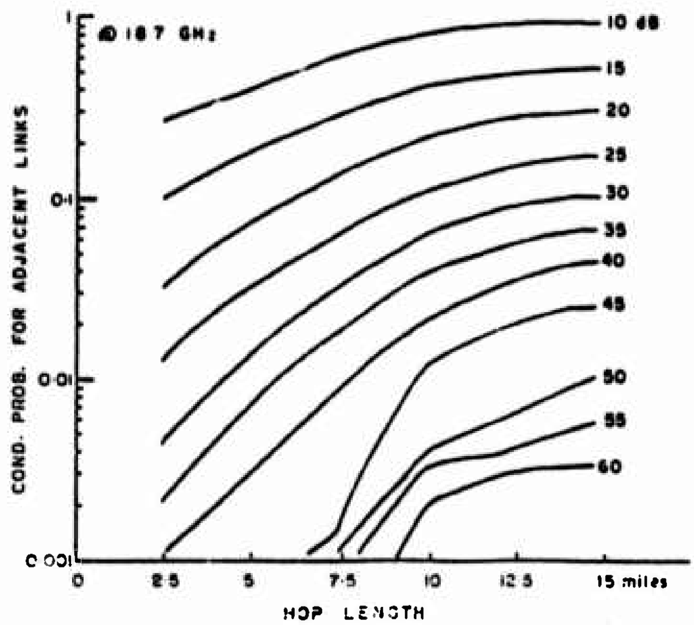


Fig. 28. Conditional probability that a given attenuation is exceeded jointly on consecutive links versus hop lengths at 18.7 GHz.

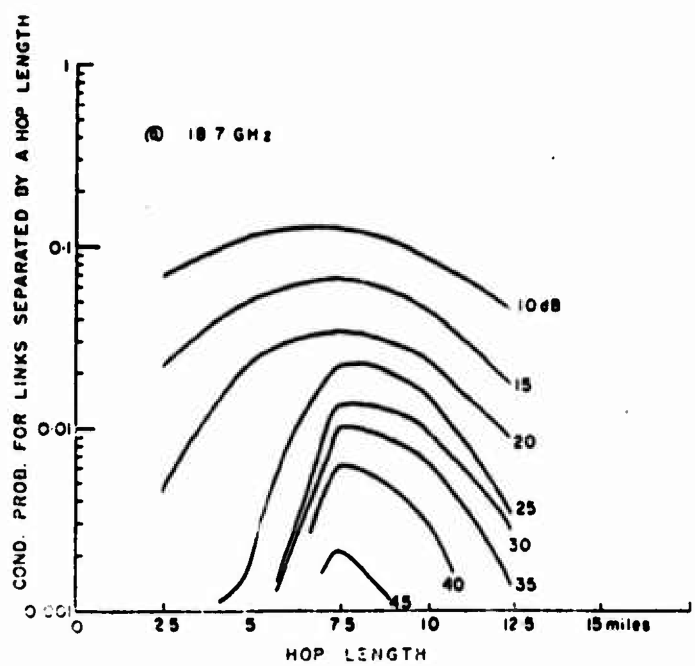
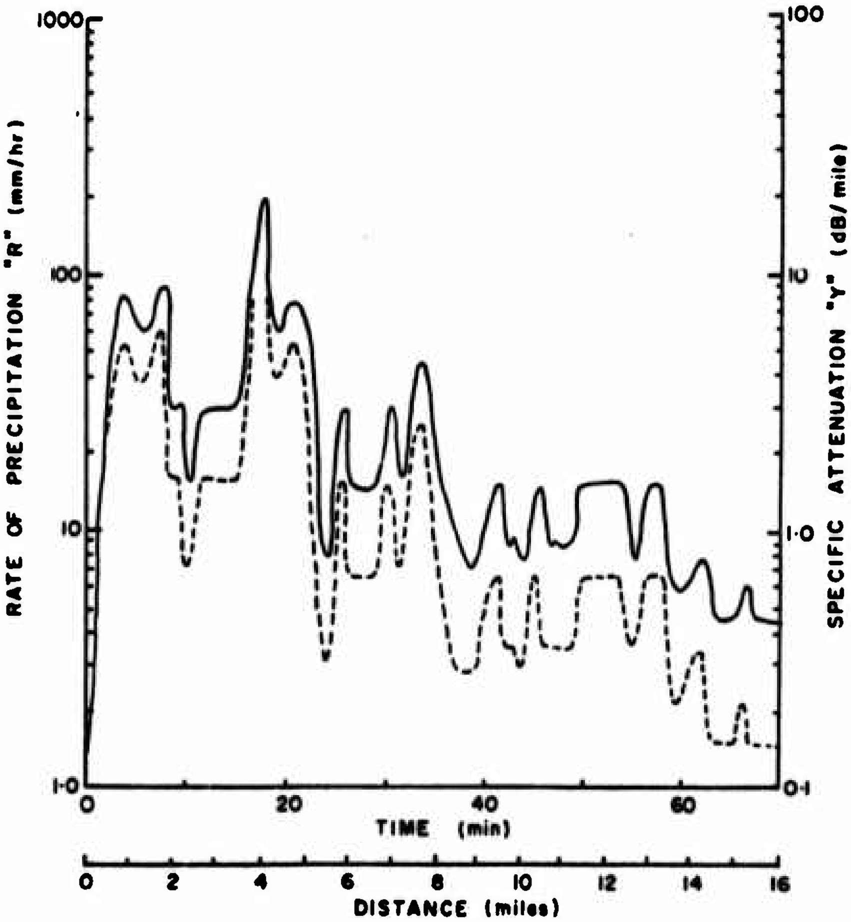


Fig. 29. Conditional probability that a given attenuation is exceeded jointly on links separated by a hop length versus hop length at 18.7 GHz.



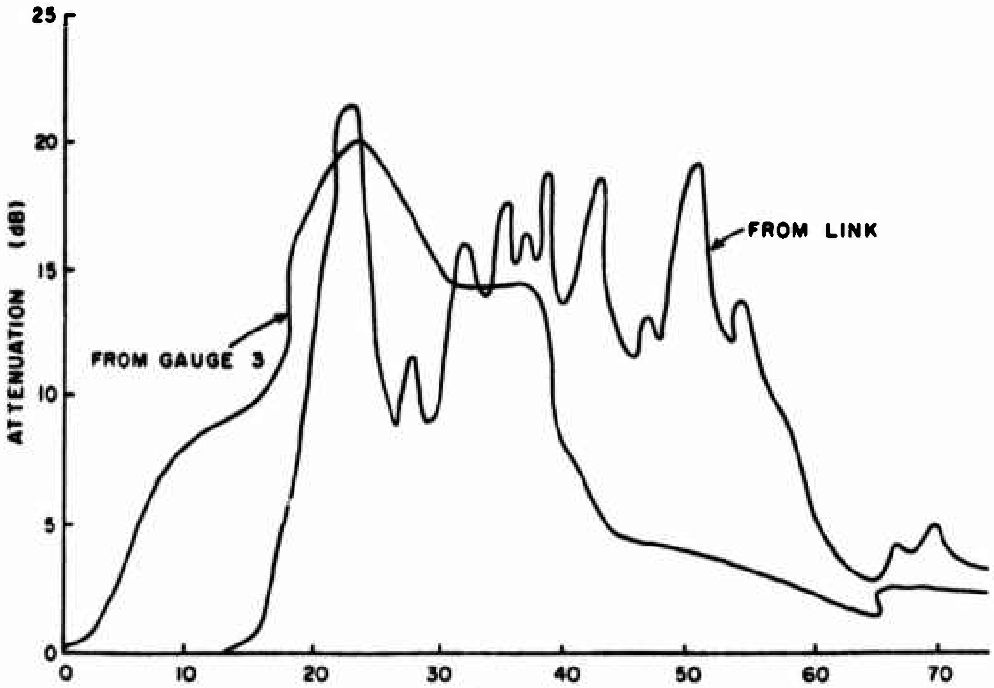


Fig. 30 (Above). Synthetic storm of the 20th August 1971 (continuous line). The dotted line refers to specific attenuation at 11.2 GHz.

Fig. 31 (Below). The storm of Fig. 30 has been used to calculate the attenuation for a 5-mile link at 11.2 GHz. For comparison the actual attenuation experienced by this link is plotted. Note the coincidence of the peak at 22 minutes. This is due to chance because the storm hit the raingauge with its maximum intensity.

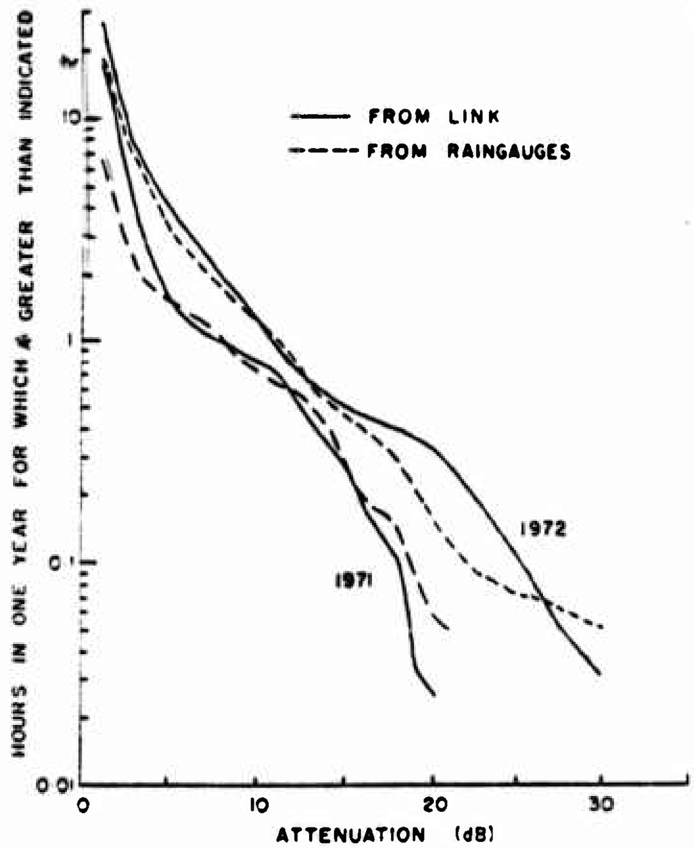
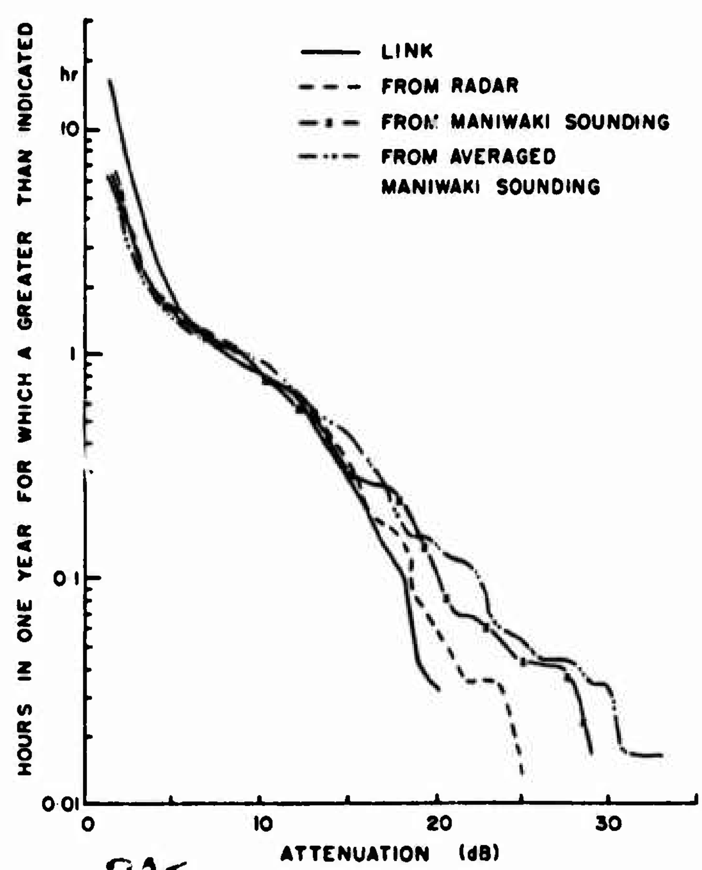


Fig. 32. Probability that a given attenuation is exceeded for a 5-mile link at 11.2 GHz as calculated from raingauge (dashed) and measured on the real link (continuous). The data are for 1971 and 1972.

Fig. 33. 1971 statistics using different estimates of the velocity of precipitation patterns. The curve with two dots is obtained using one value of velocity for the entire summer. This is to show the relative insensitivity of the results to the velocity used in the calculations.



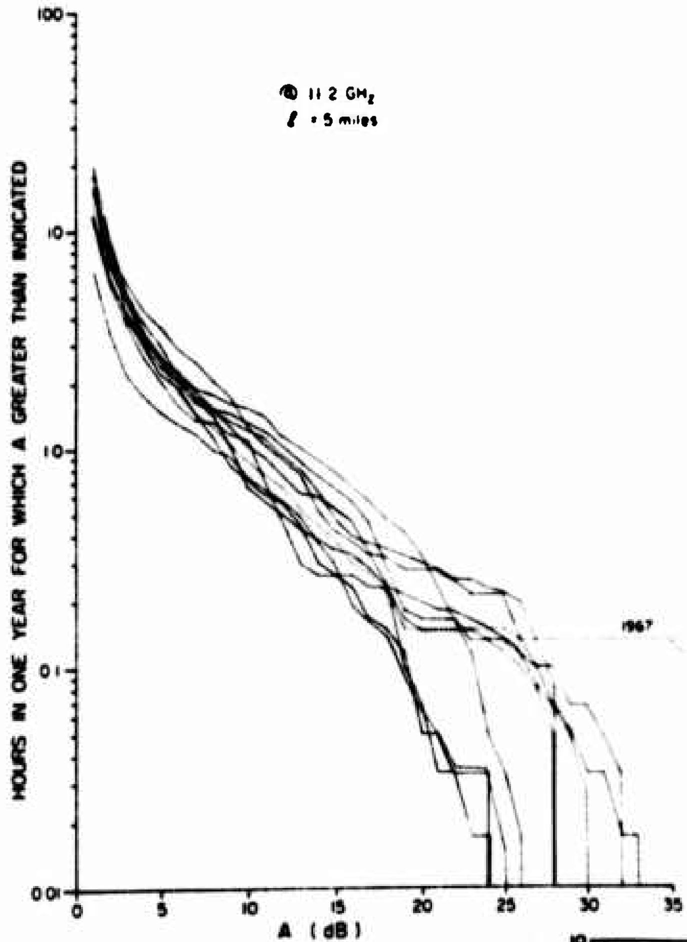


Fig. 34. Probabilities that a given attenuation is exceeded at 11.2 GHz for 5-mile link for 10 years in Montreal.

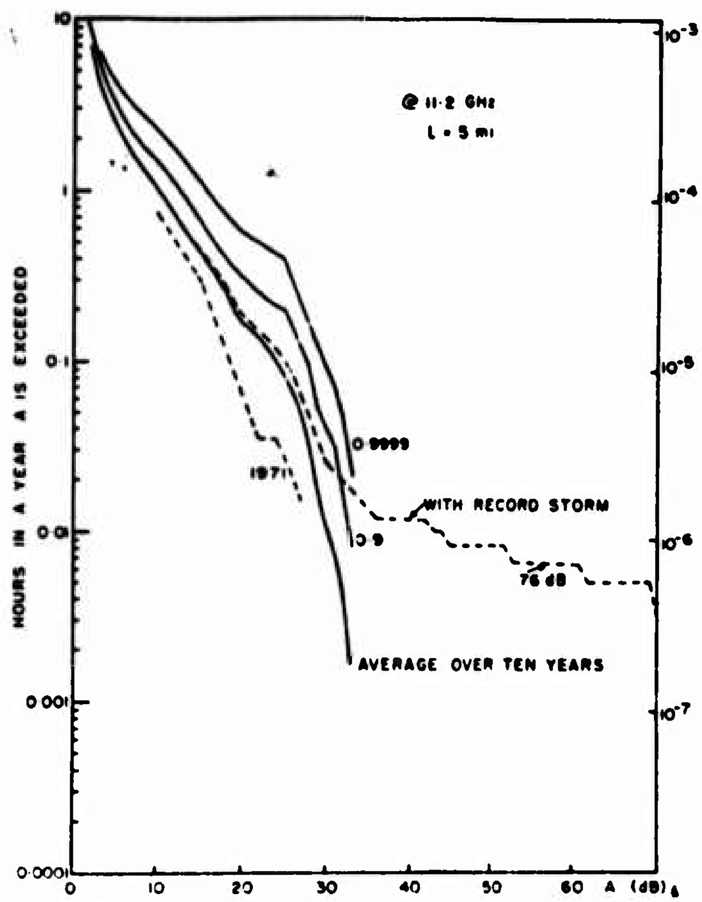
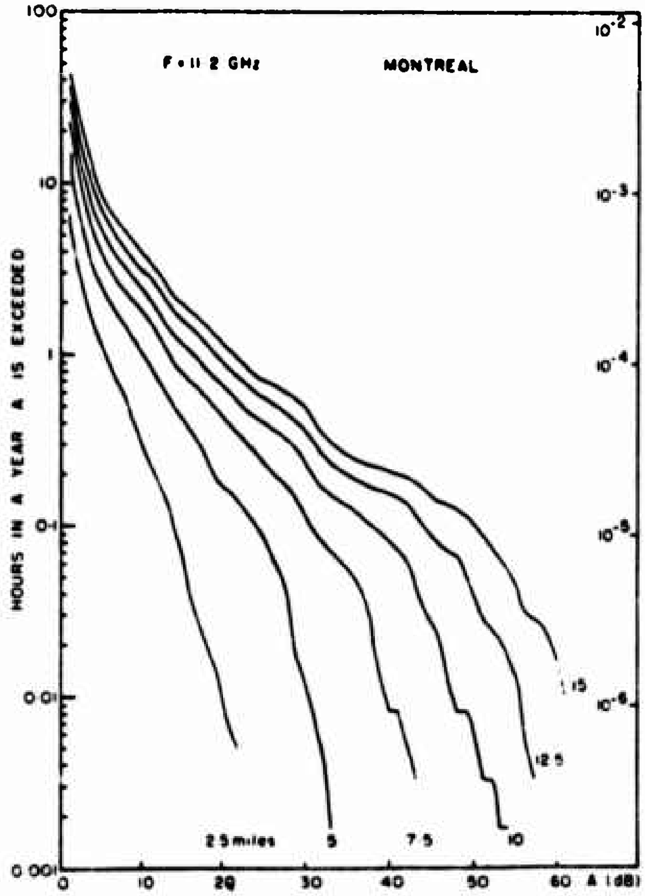
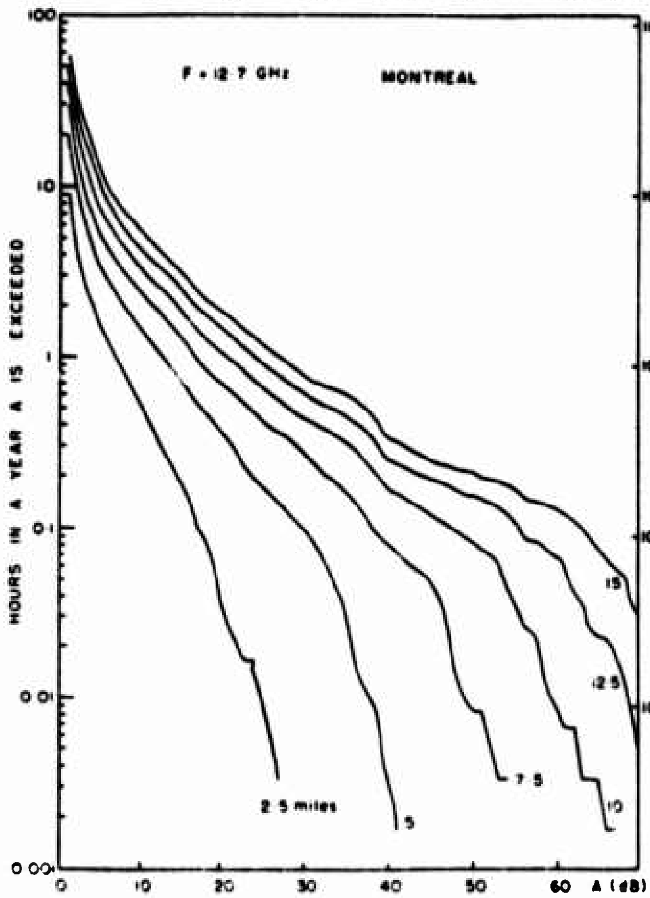
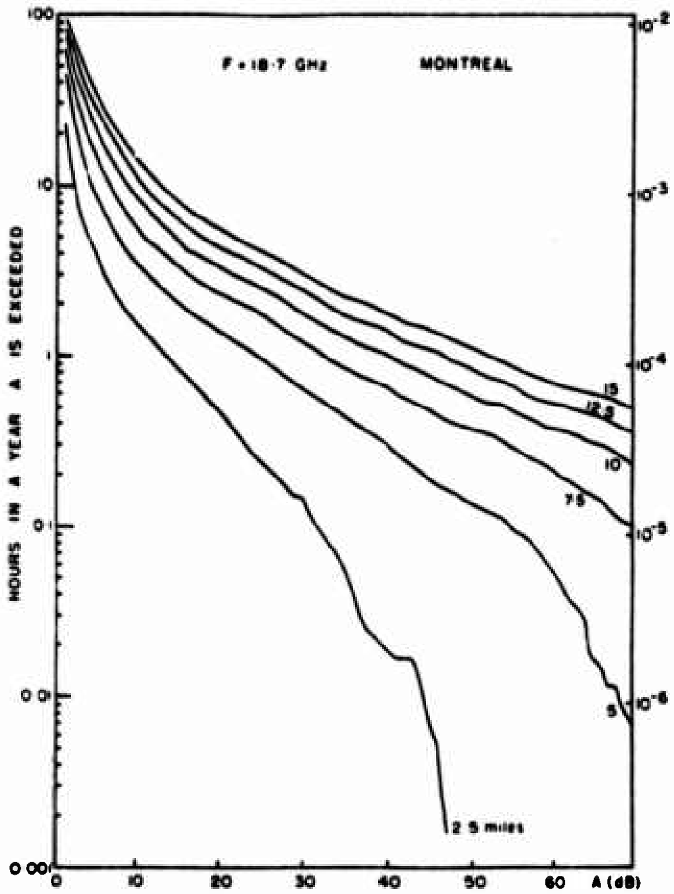


Fig. 35. Probability that a given attenuation is exceeded at 11.2 GHz for 5-mile link for a 10 year period. The curves labelled 0.9 and 0.9999 correspond to 10% and .01% of the population assumed to be gaussian.

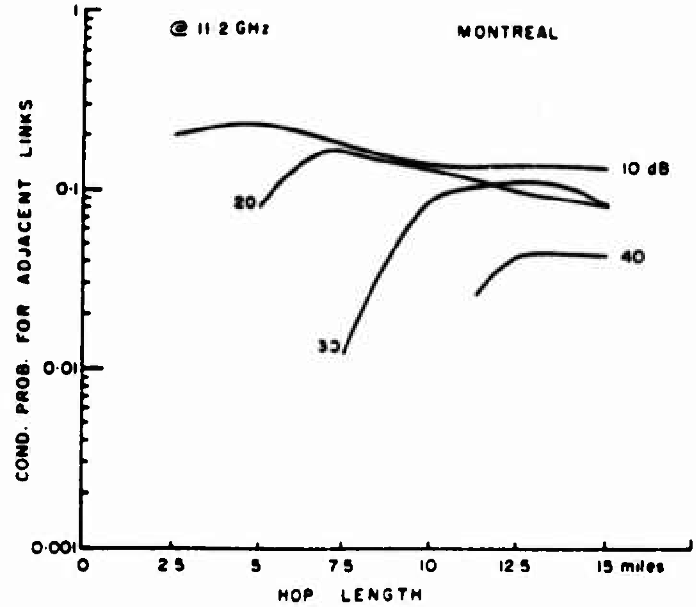

F = 11.2 GHz
MONTREAL
HOURS IN A YEAR A IS EXCEEDED
2.5 miles
5
7.5
10
12.5
15
A (dB)

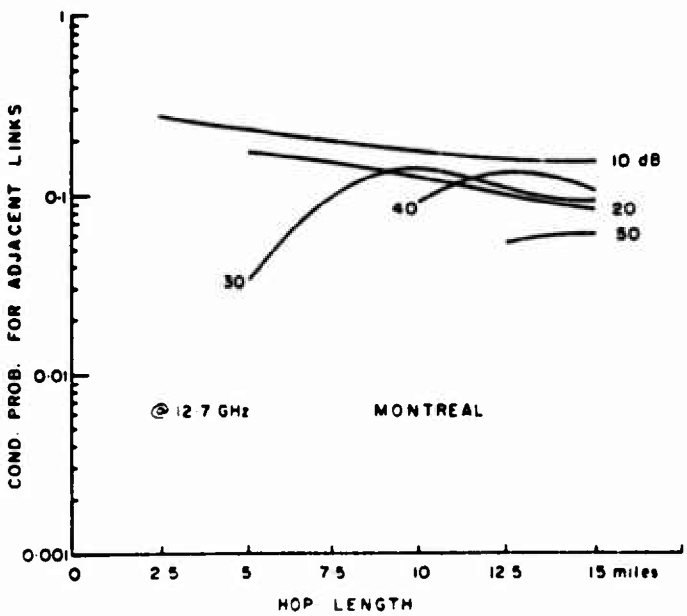

F = 12.7 GHz
MONTREAL
HOURS IN A YEAR A IS EXCEEDED
2.5 miles
5
7.5
10
12.5
15
A (dB)

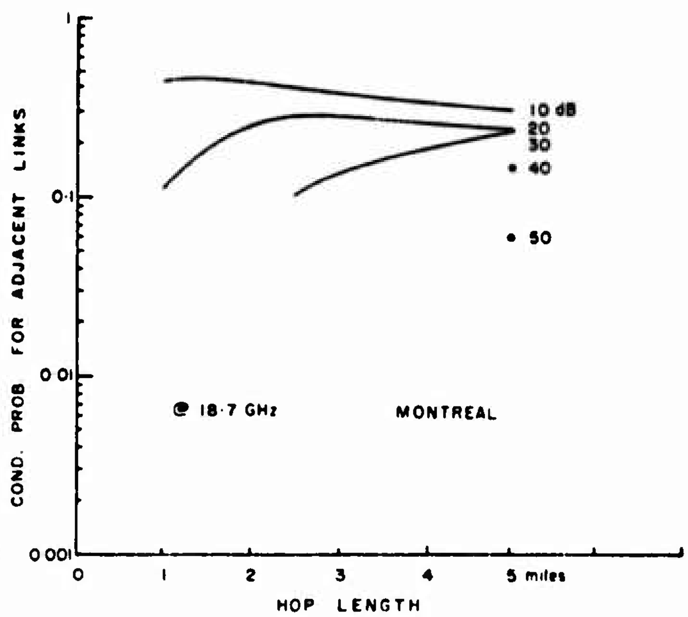


Figs. 36,37,38 (Top Left; Bottom Left; Above). Probability that a given attenuation is exceeded at 11.2, 12.7, 18.7 GHz for various hop lengths. The curves are obtained averaging 10 years of data.

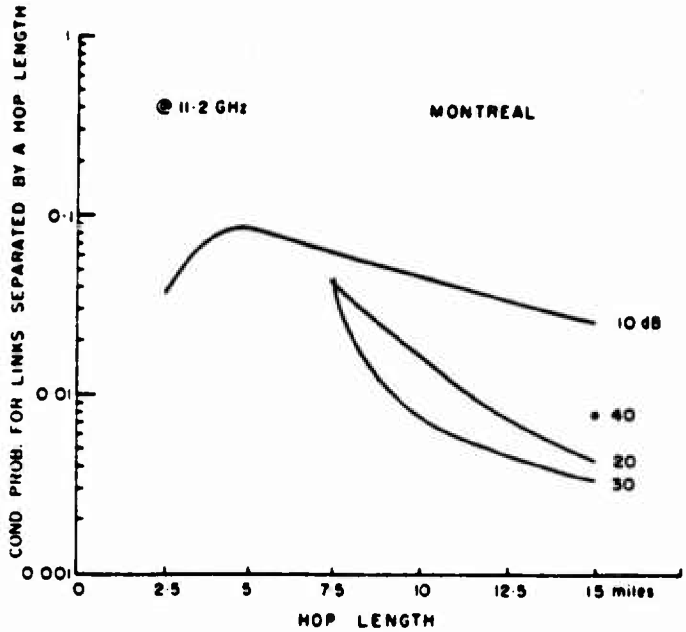
Figs. 39,40,41 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on adjacent links at 11.2, 12.7, and 18.7 GHz.

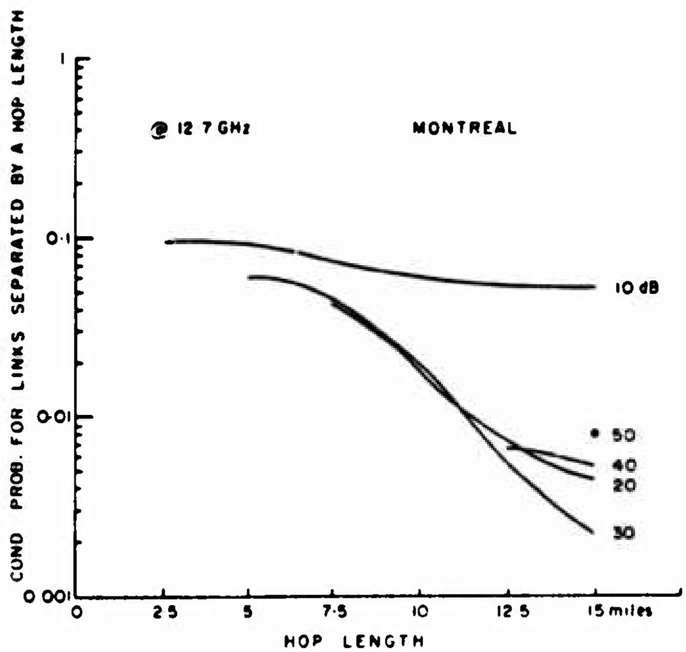


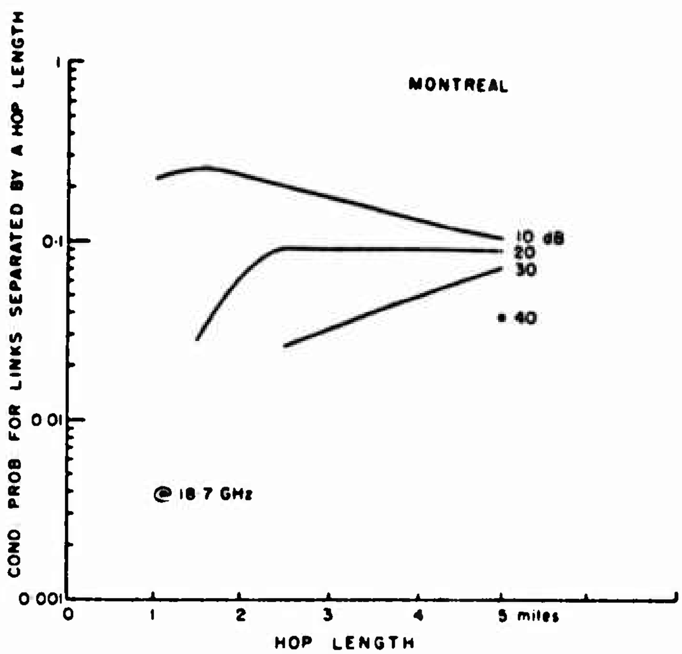




Figs. 42,43,44 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on two links separated by a link length at 11.2, 12.7, 18.7 GHz.







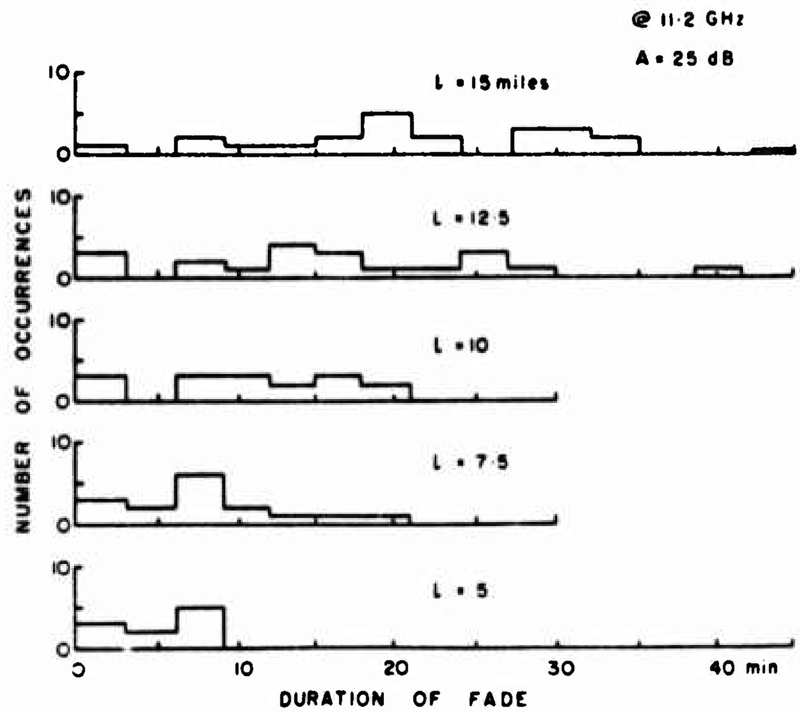


Fig. 45. Histograms of durations of 25 dB attenuation events at 11.2 GHz for various hop lengths in 10 years.

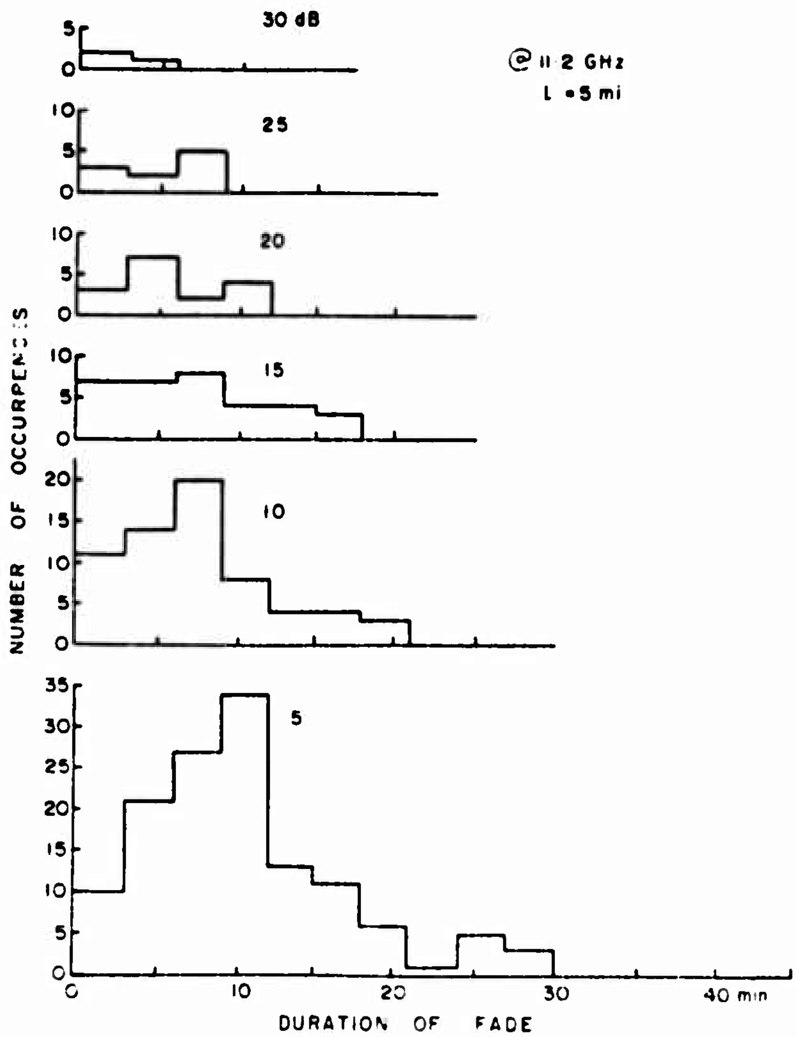
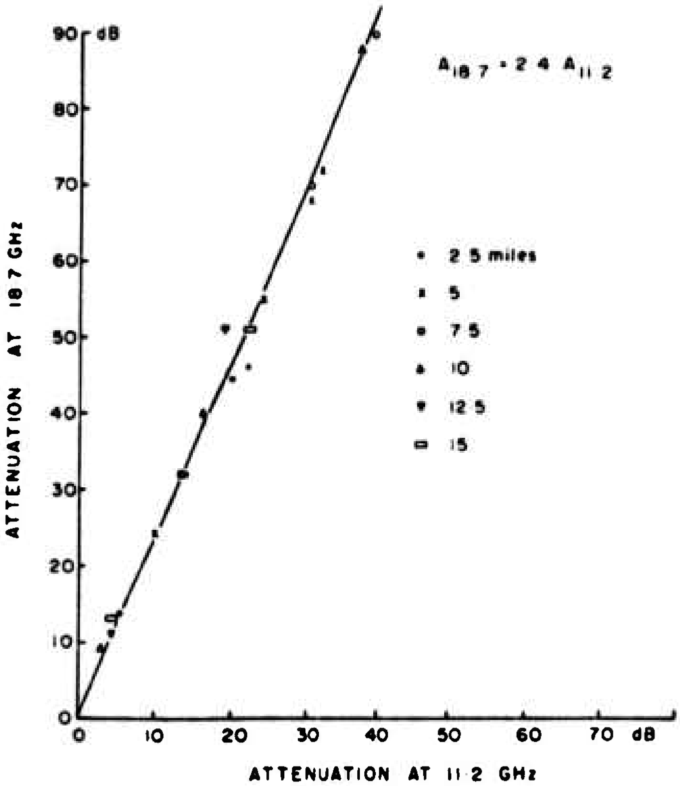
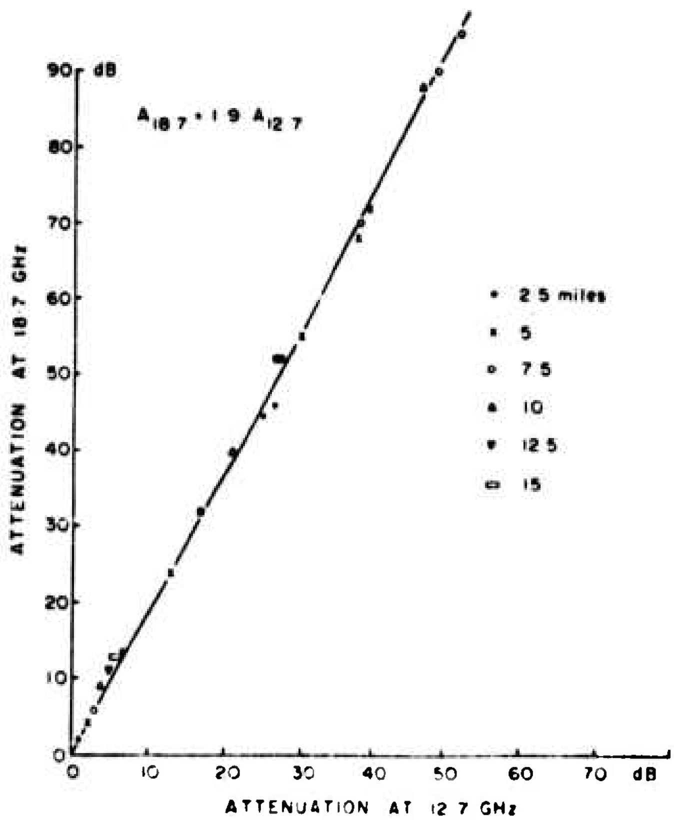
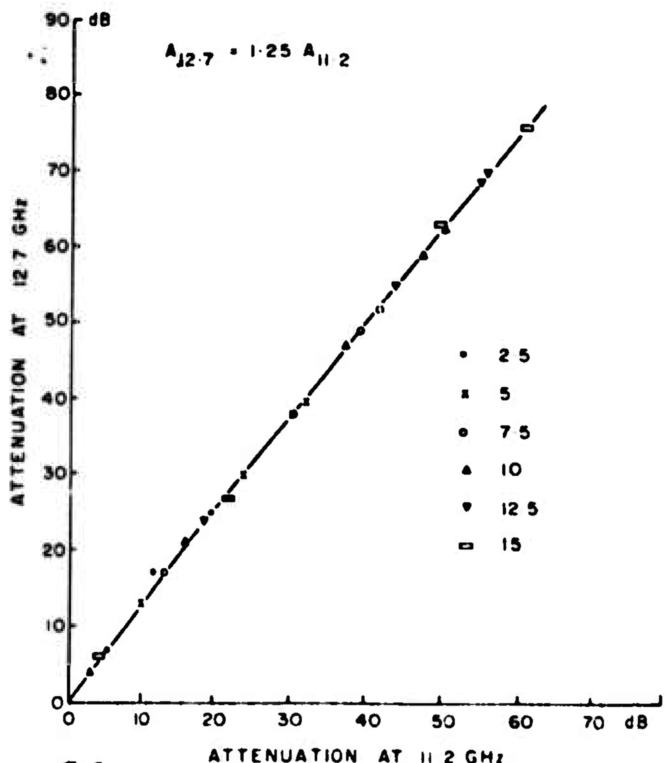


Fig. 46. Histograms of durations of events at a given attenuation for a 5 mile link at 11.2 GHz in 10 years.

Figs. 47,48,49 (Left; Below Left; Below Right). Correlogram of attenuation events at 11.2, 12.7, 18.7 GHz. The events have the same probability level and are for the same hop length.







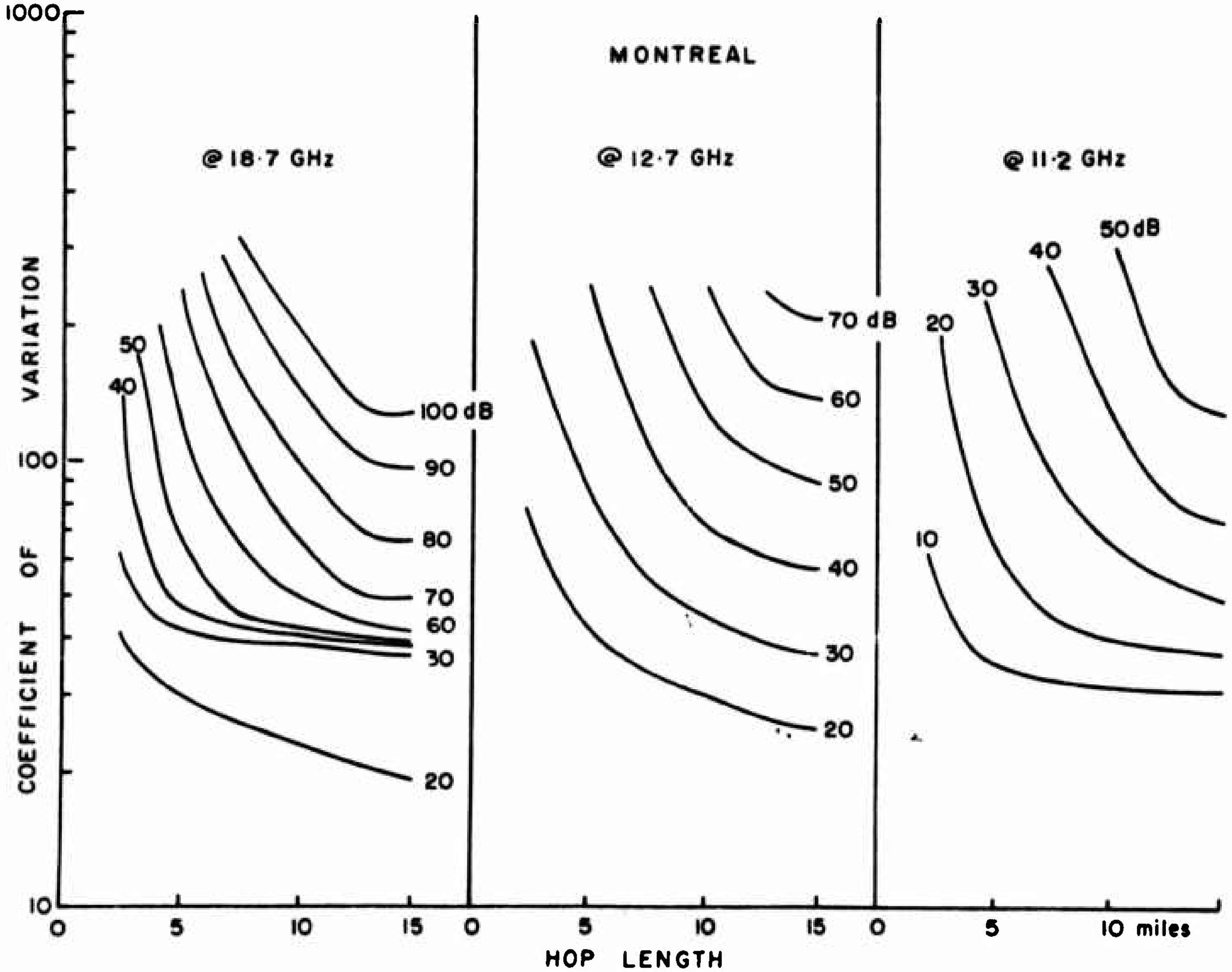


Fig. 50. Coefficient of variation of the yearly probability that a given attenuation is exceeded versus hop length for 11.2, 12.7, and 18.7 GHz.

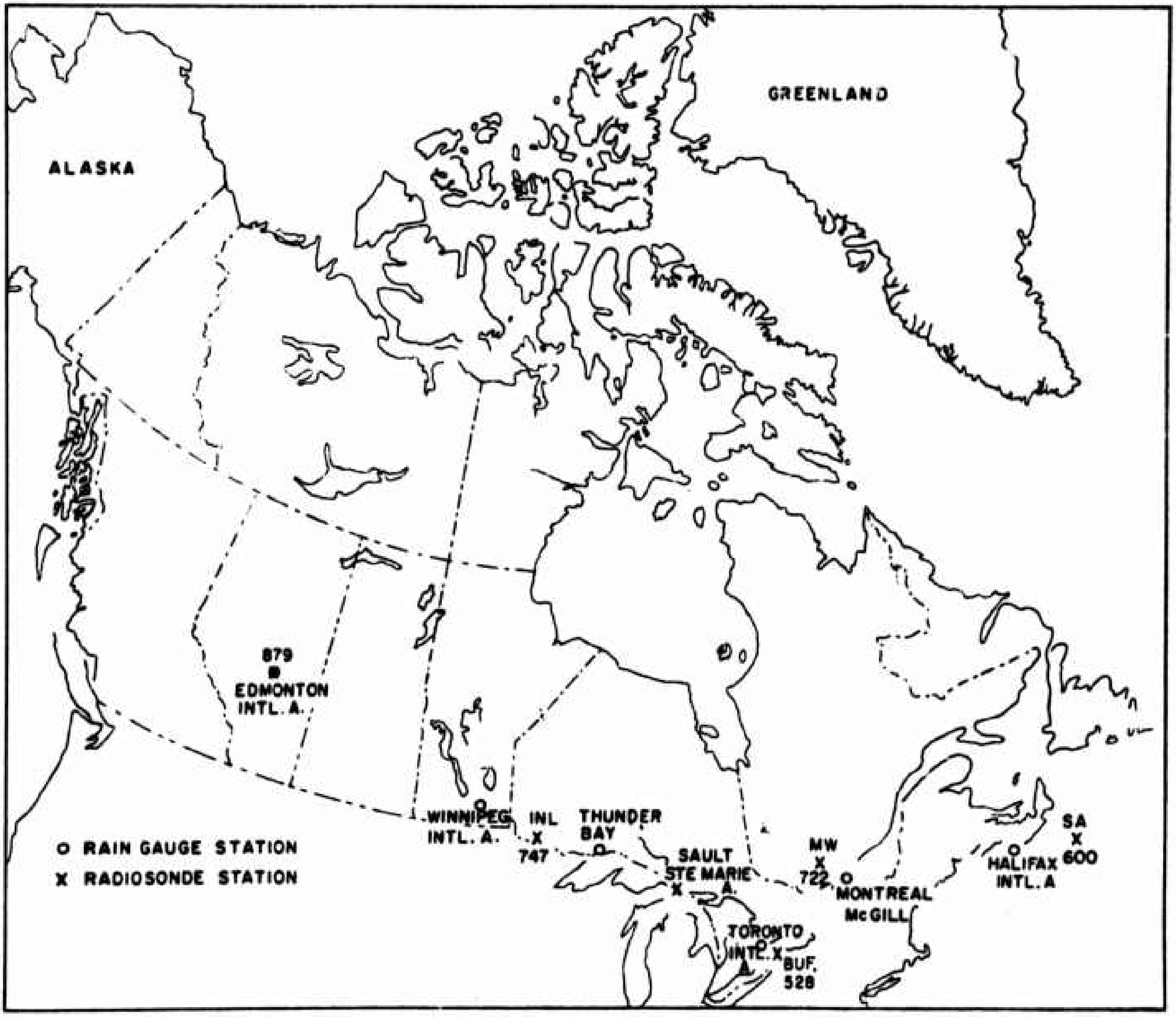


Fig. 51. Map of Canada showing the location of the raingauge stations and rawinsonde stations considered in this study.

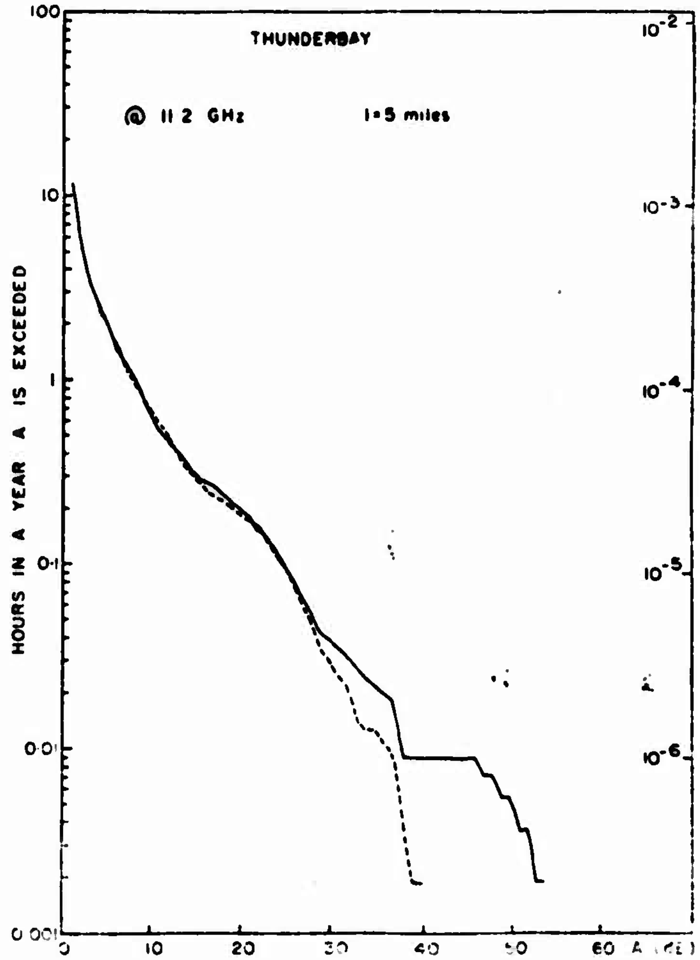
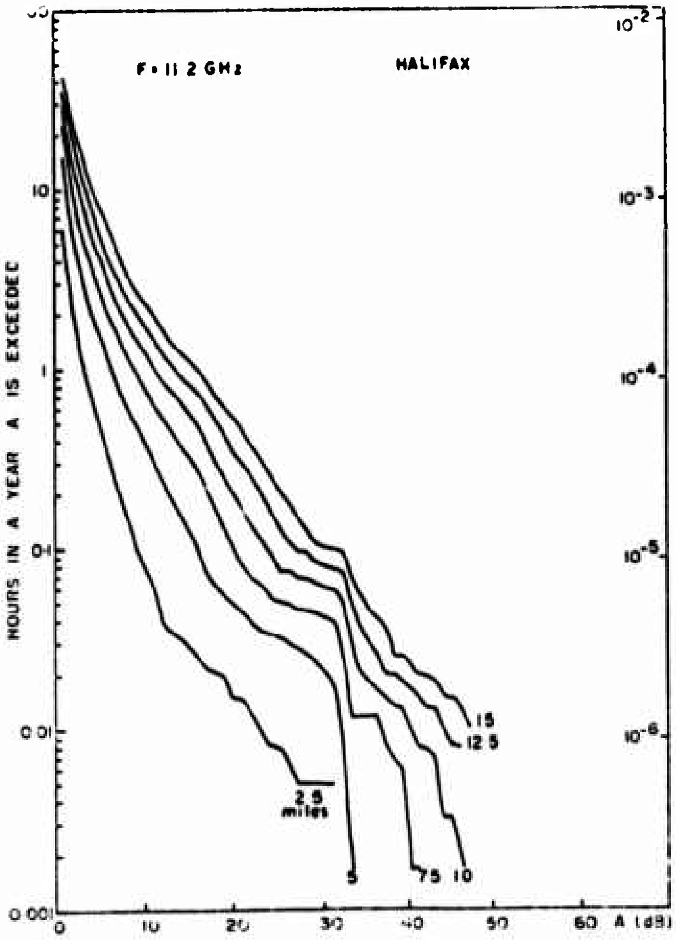
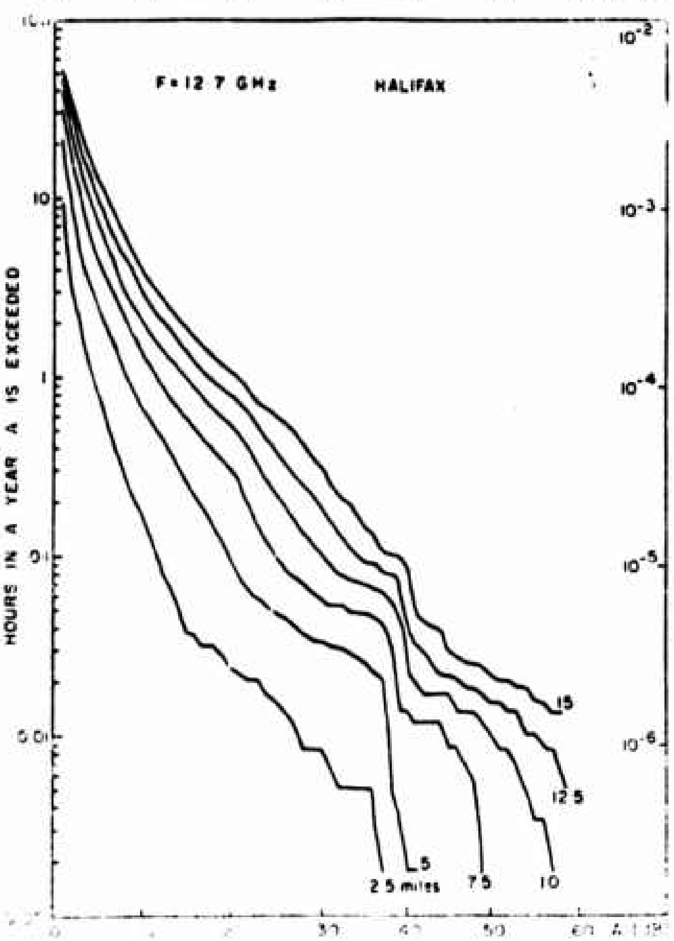
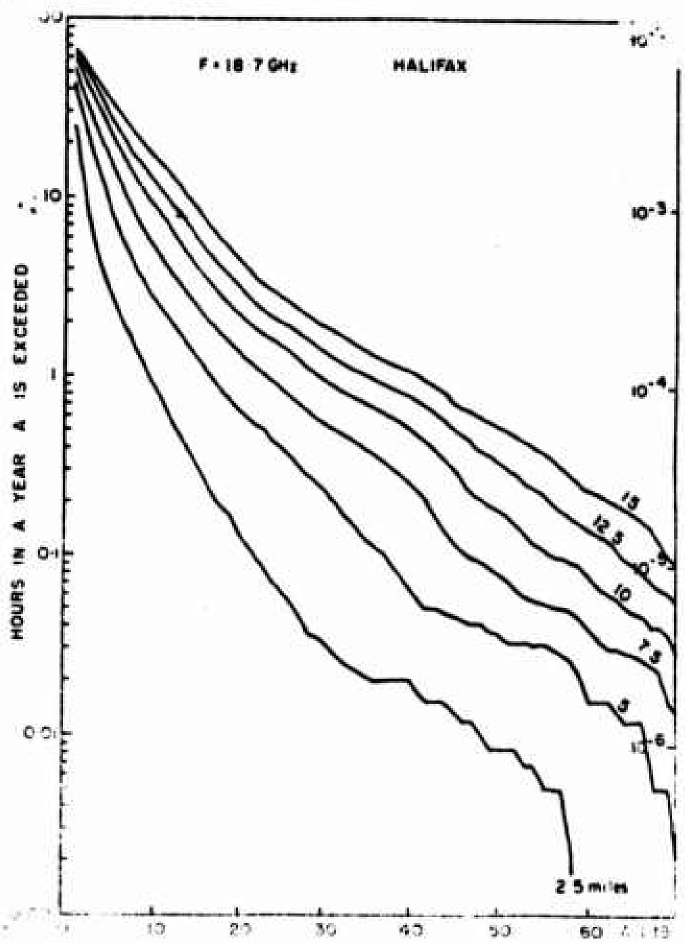


Fig. 52. Probabilities of exceeding a given attenuation for a 5-mile link at 11.2 GHz. The two curves are calculated using wind velocities from International Falls (continuous) and Sault Ste. Marie (dotted).

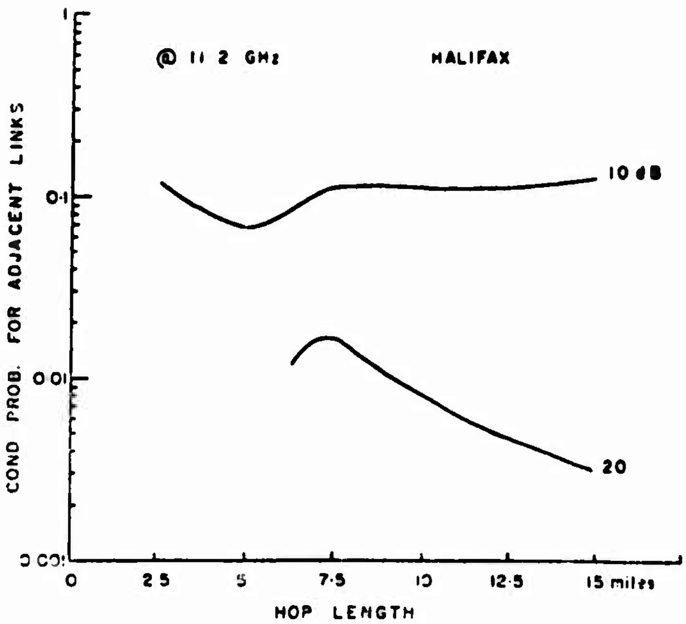


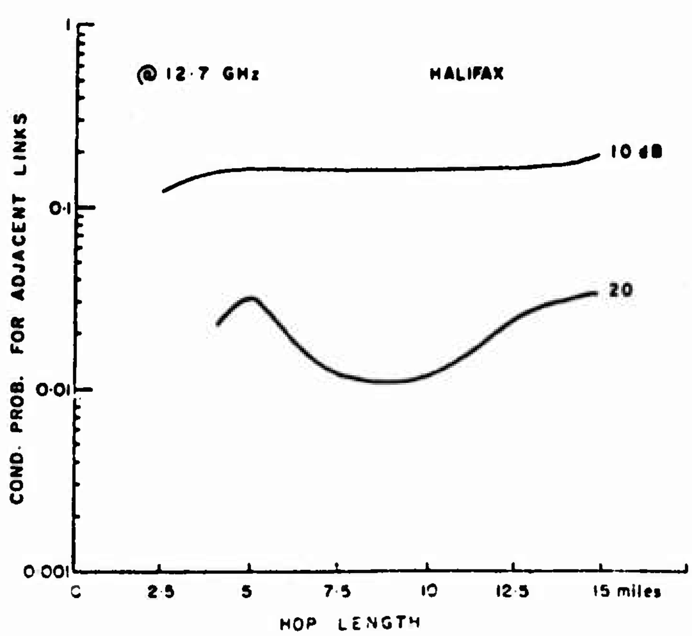
Figs. 53,54,55 (Left; Below Left; Below Right). Probability that a given attenuation is exceeded at 11.2, 12.7, and 18.7 GHz for various hop lengths. The curves are obtained averaging 10 years of data.

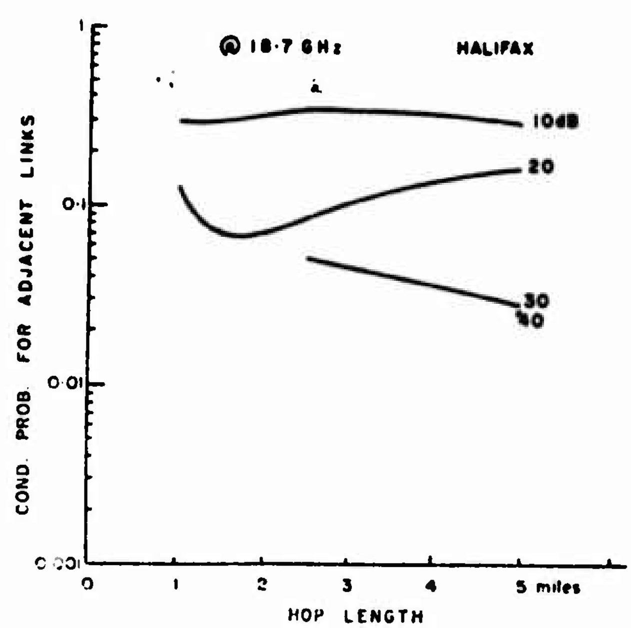


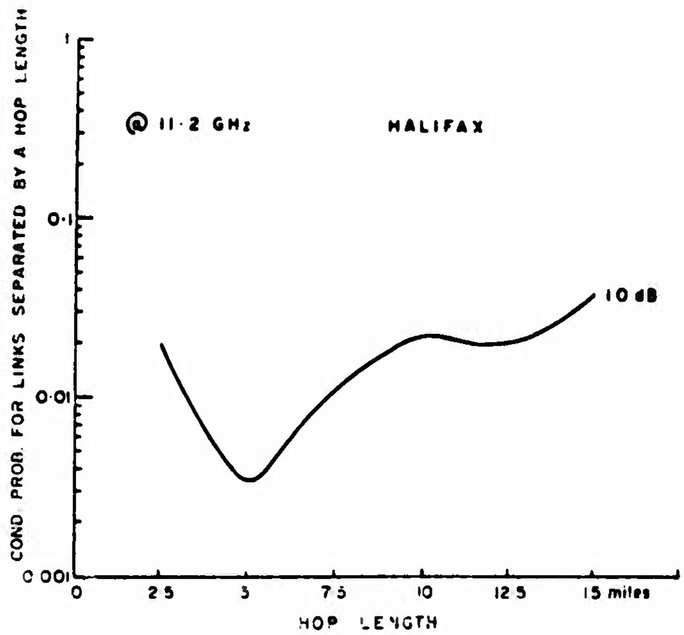


Figs. 56,57,58 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on adjacent links at 11.2, 12.7 and 18.7 GHz.

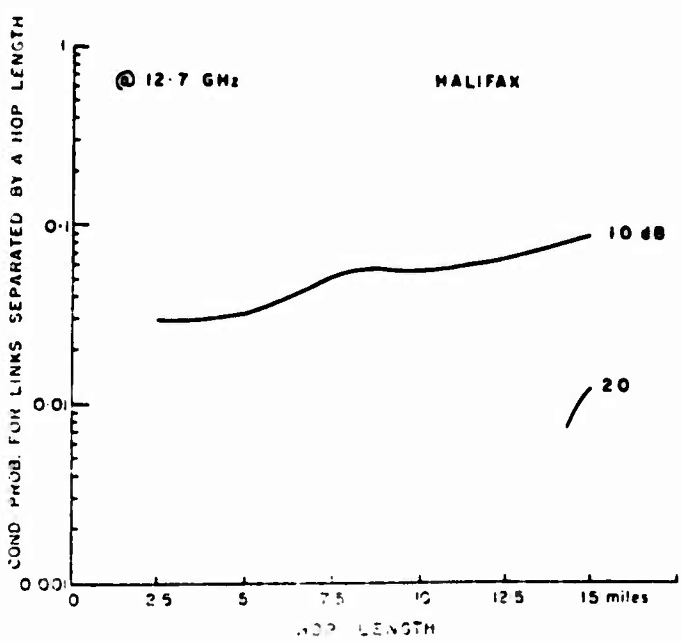


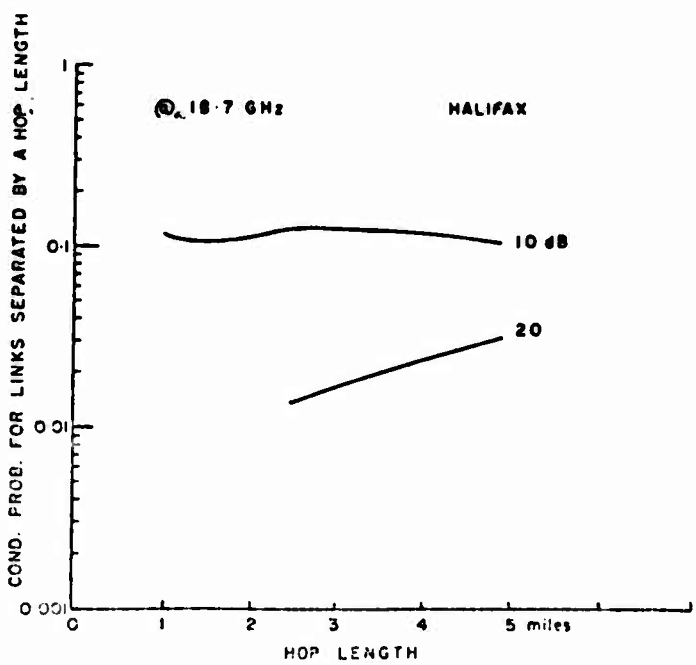






Figs. 59,60,61 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on two links separated by a link length at 11.2, 12.7 and 18.7 GHz.





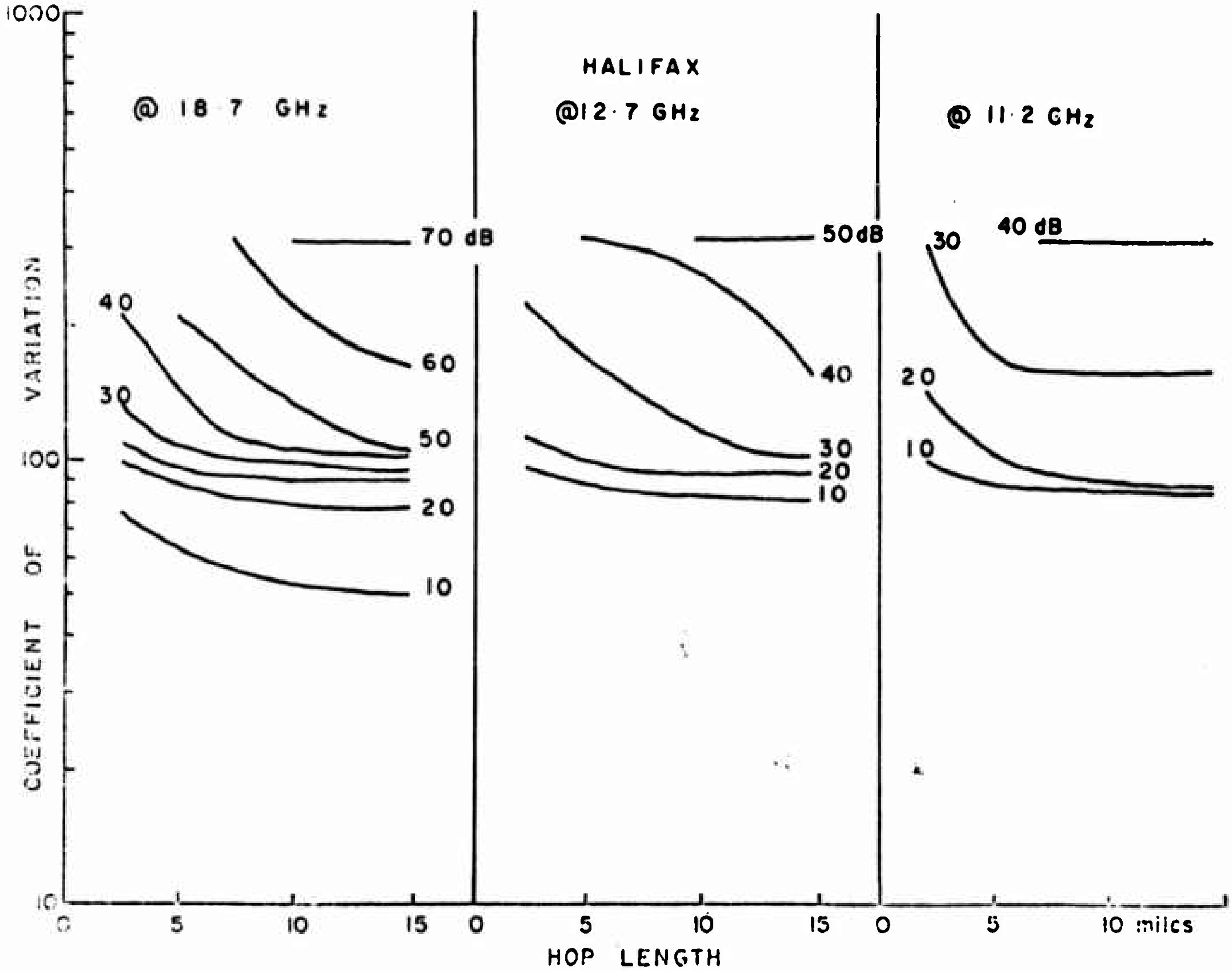
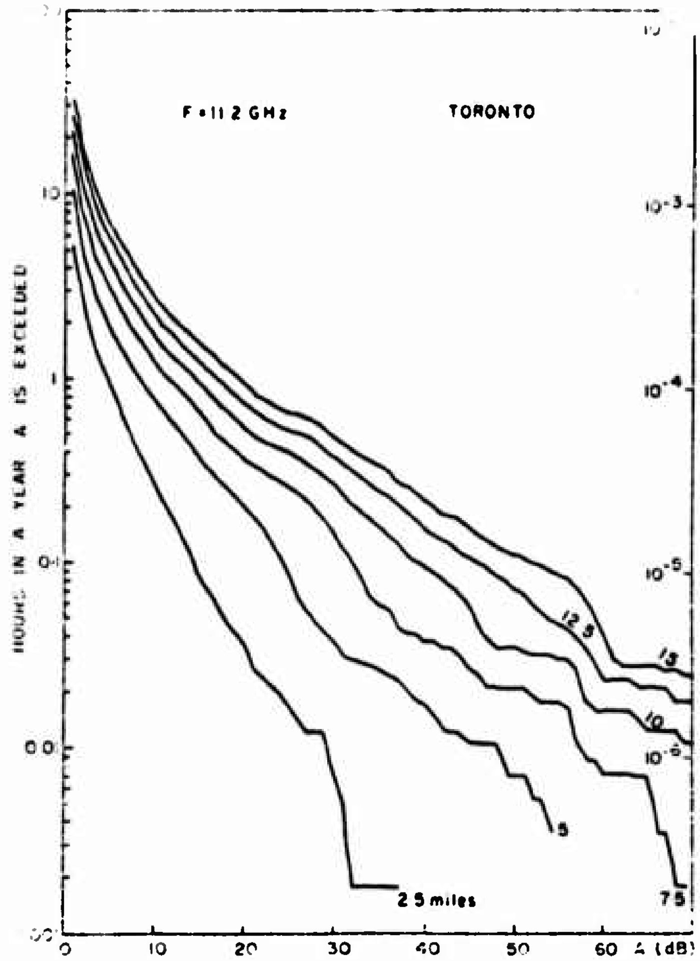
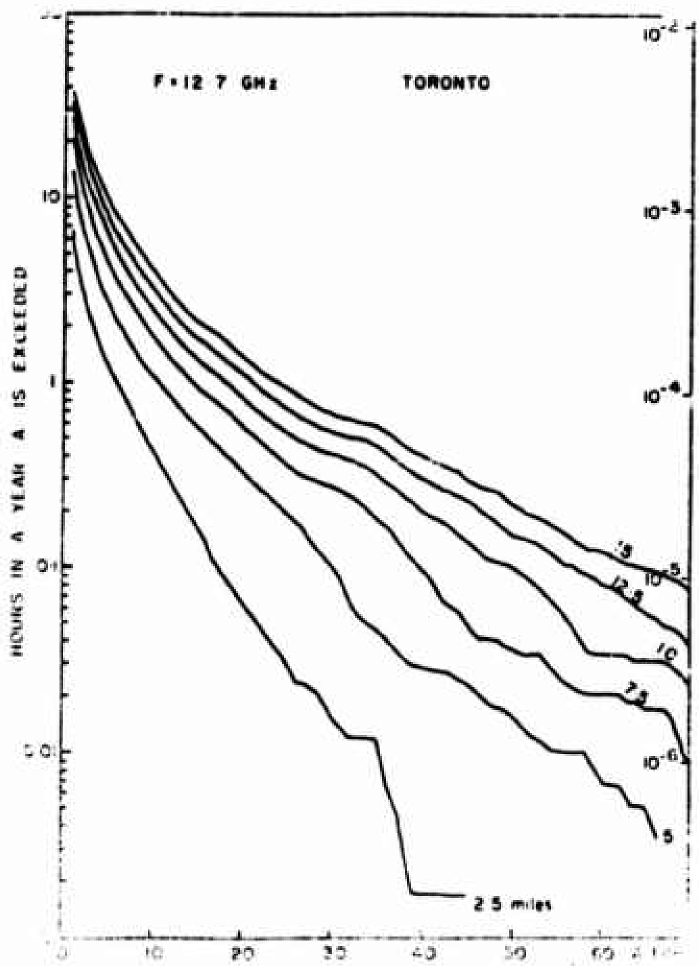
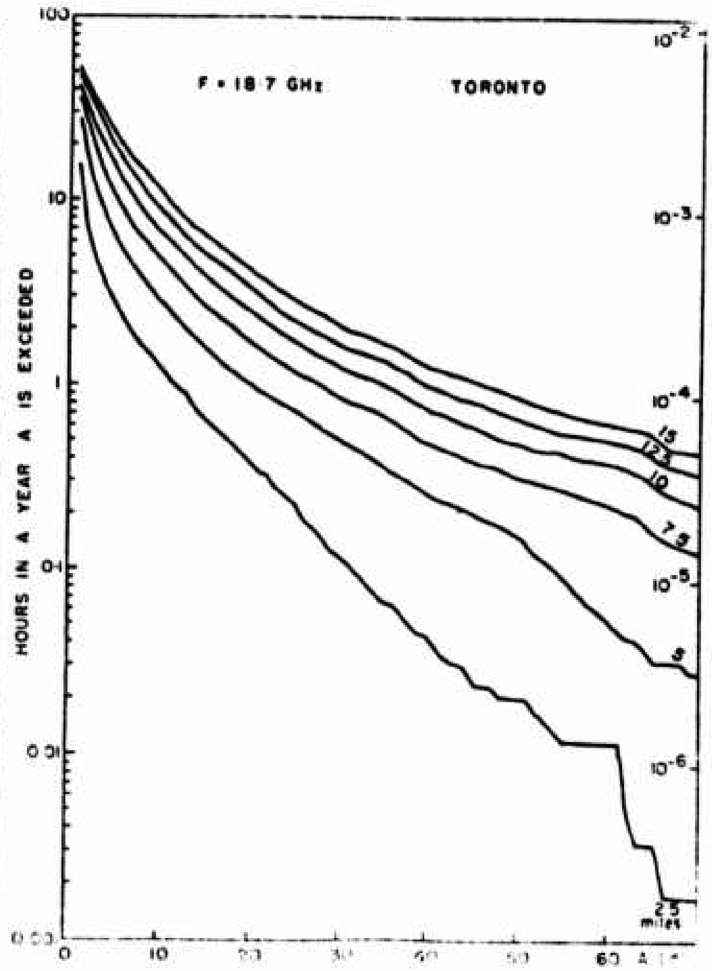


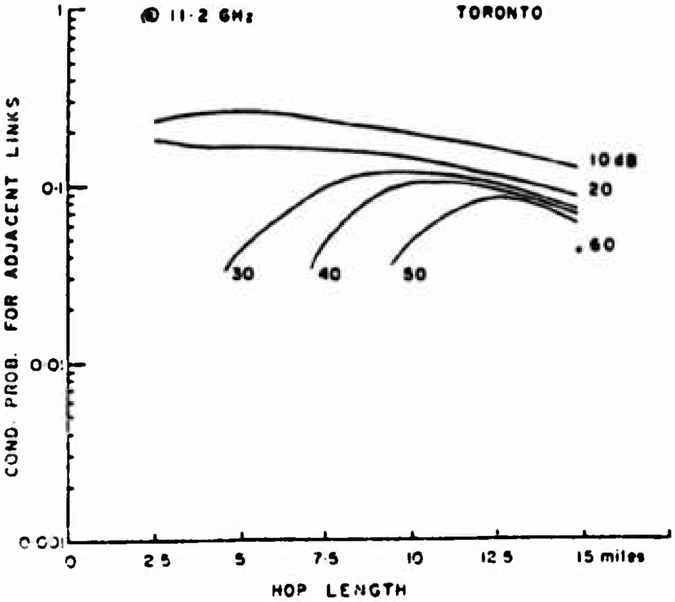
Fig. 62. Coefficient of variation of the yearly probability that a given attenuation is exceeded versus hop length for 11.2, 12.7 and 18.7 GHz.

Figs. 63,64,65 (Left; Below Left; Below Right). Probability of exceeding a given attenuation at 11.2, 12.7 and 18.7 GHz for various hop lengths. The curves are obtained averaging 10 years of data.

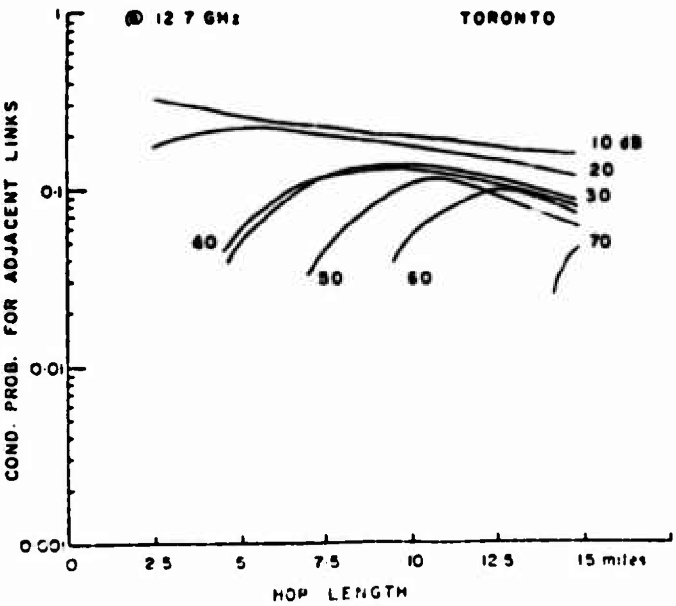


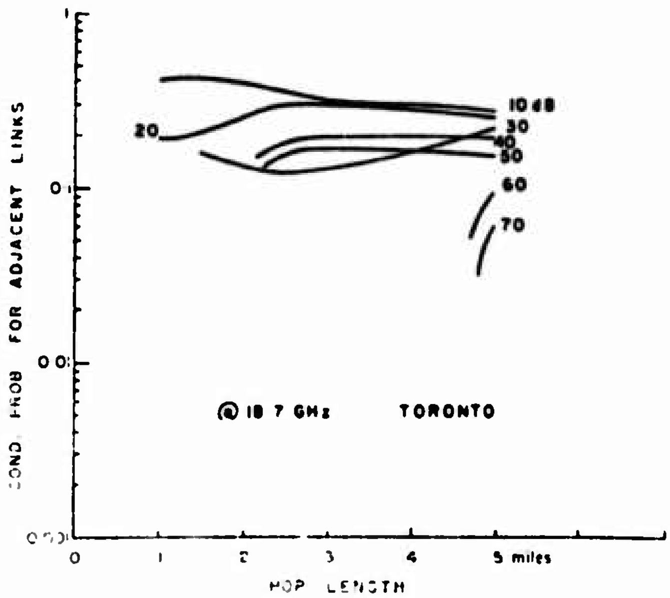


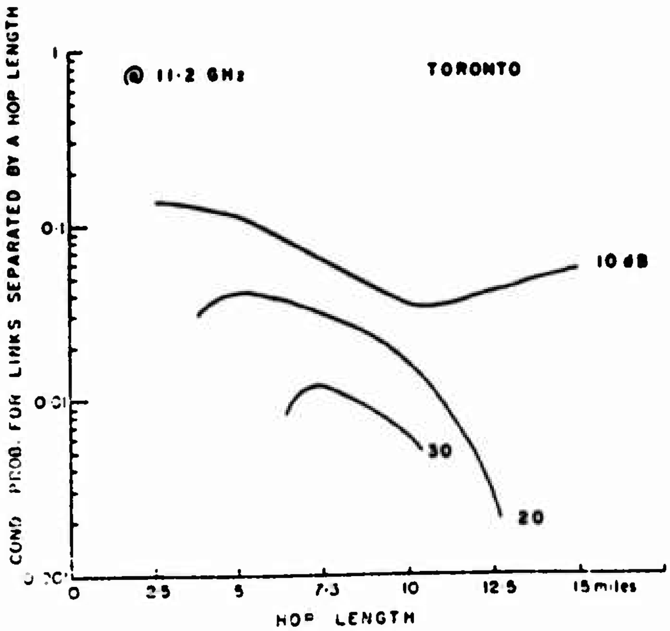




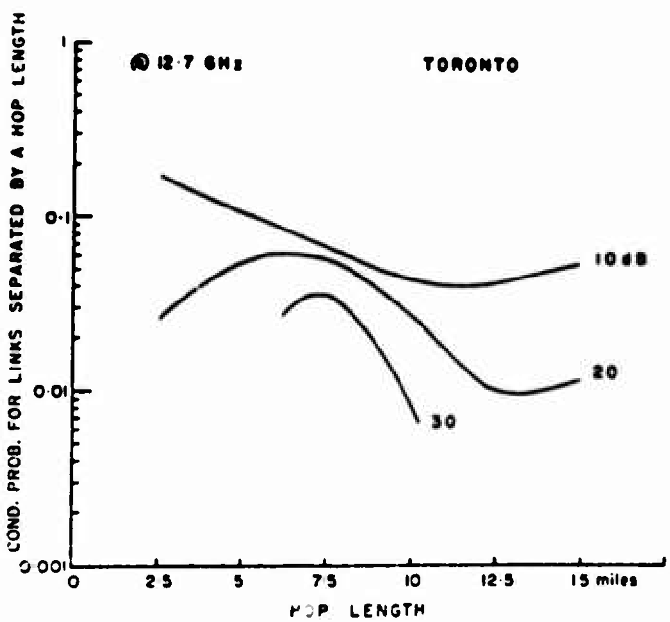
Figs. 66,67,68 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on adjacent links at 11.2, 12.7 and 18.7 GHz.

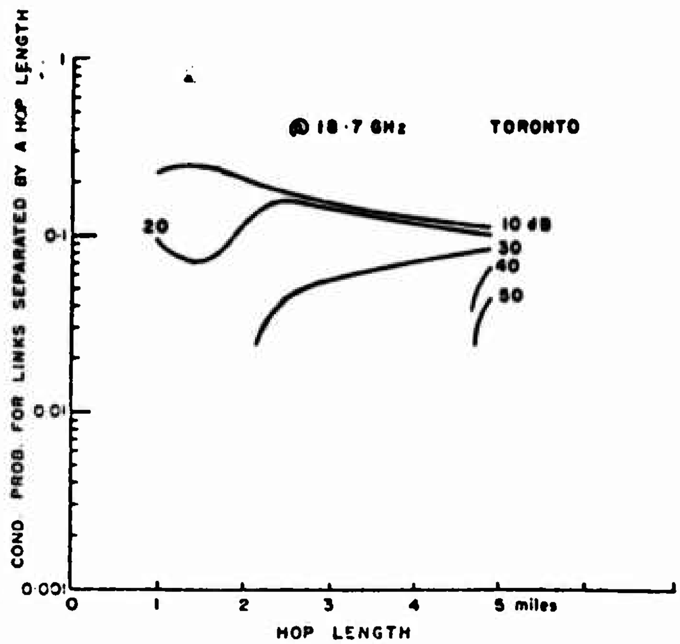






Figs. 69,70,71 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on two links separated by a link length at 11.2, 12.7 and 18.7 GHz.





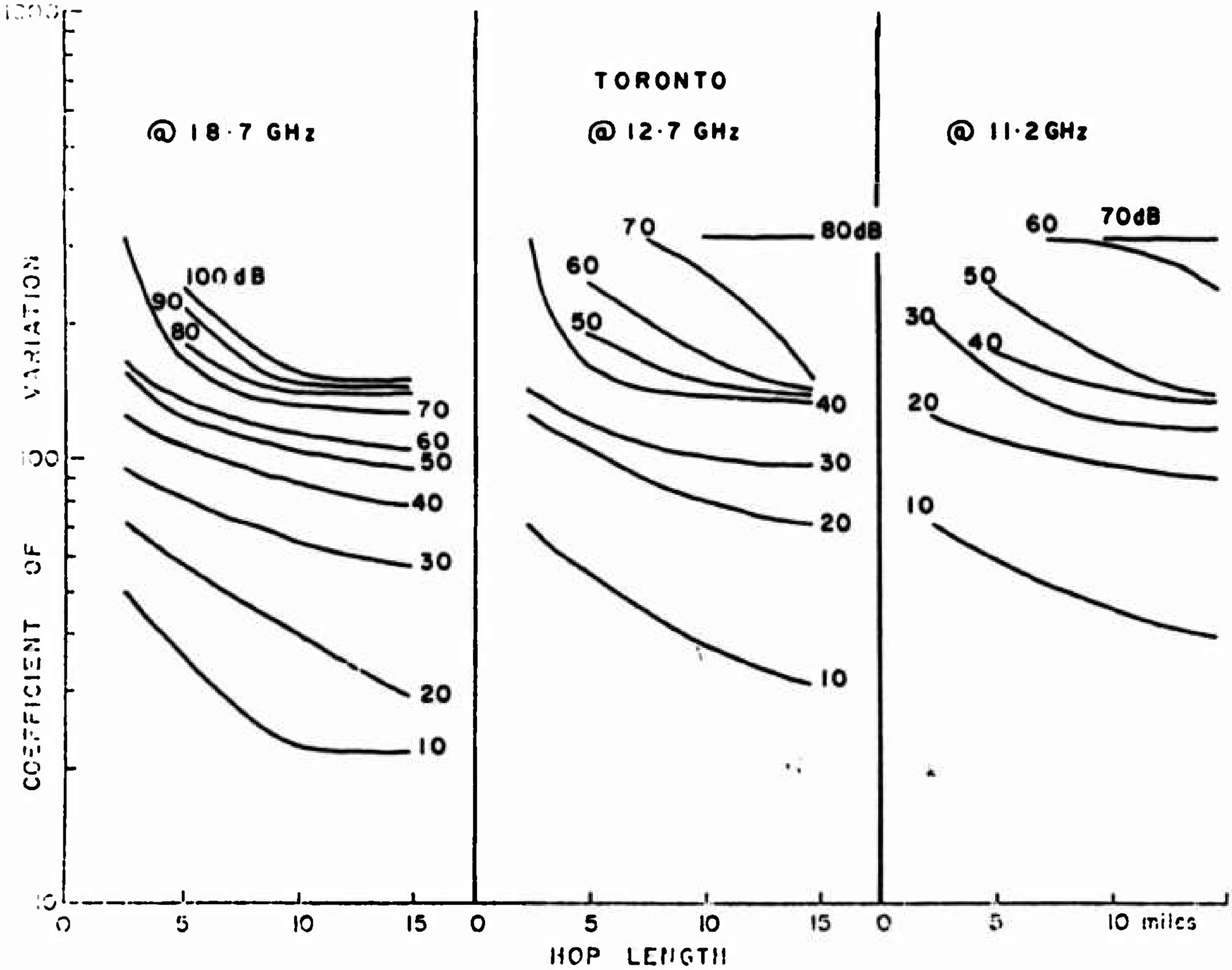
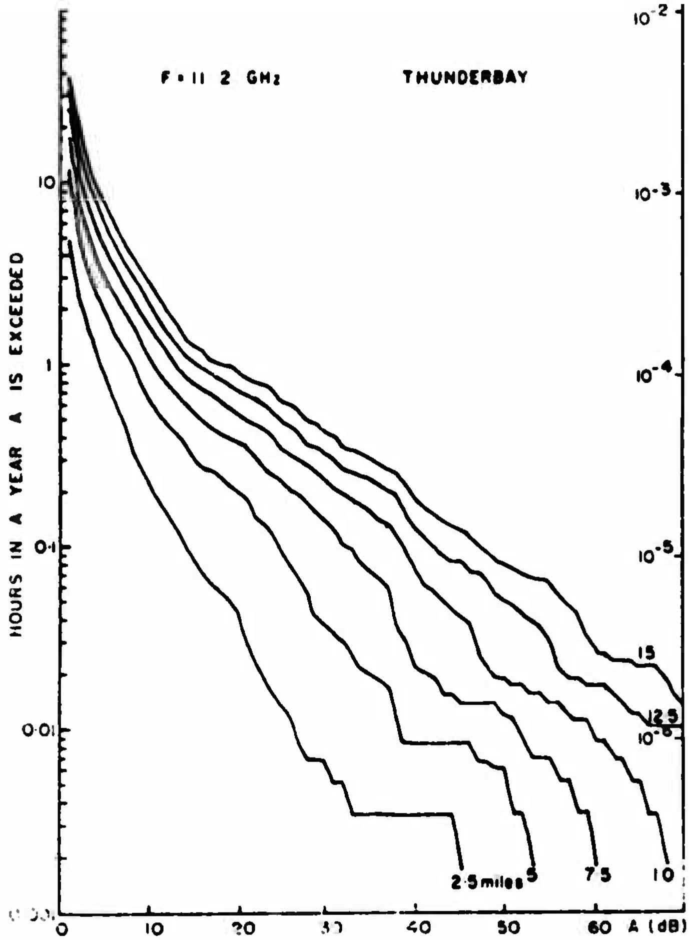
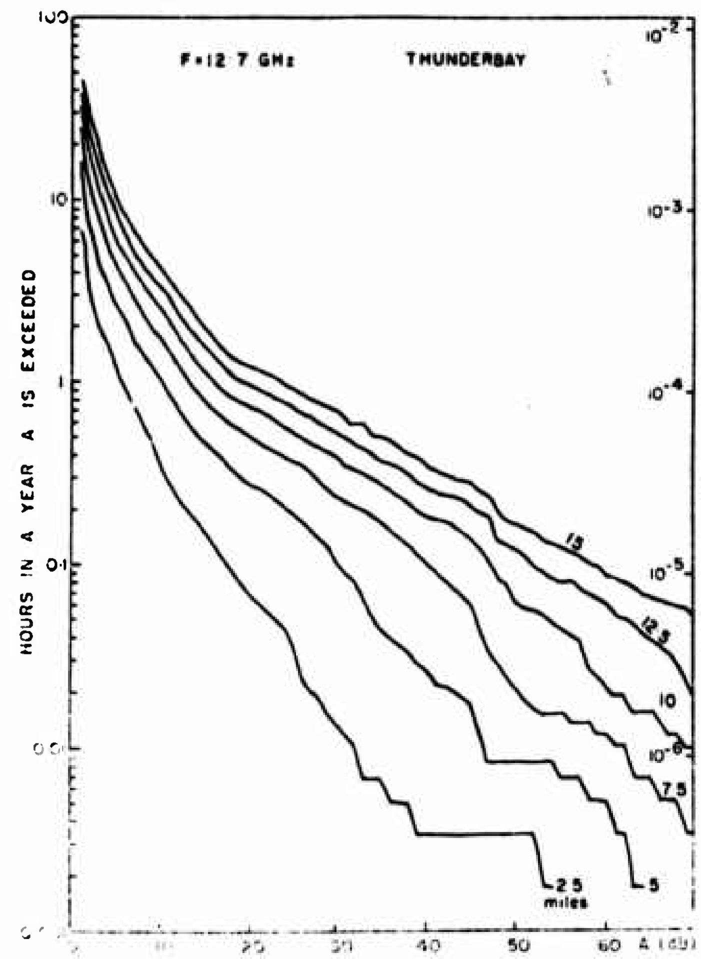
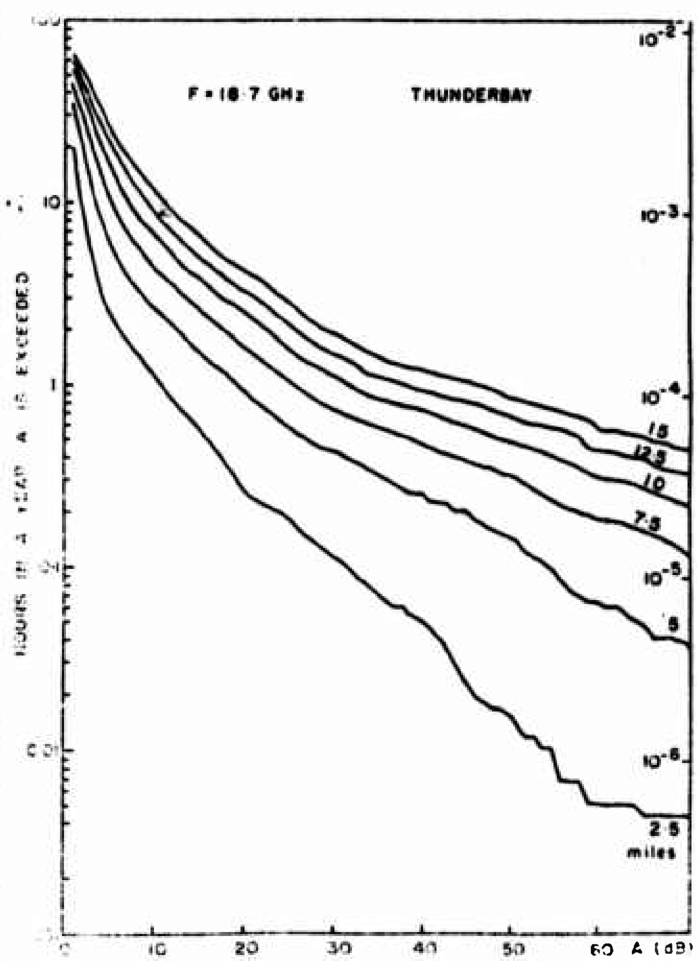


Fig. 72. Coefficient of variation of the yearly probability that a given attenuation is exceeded versus hop length for 11.2, 12.7 and 18.7 GHz.

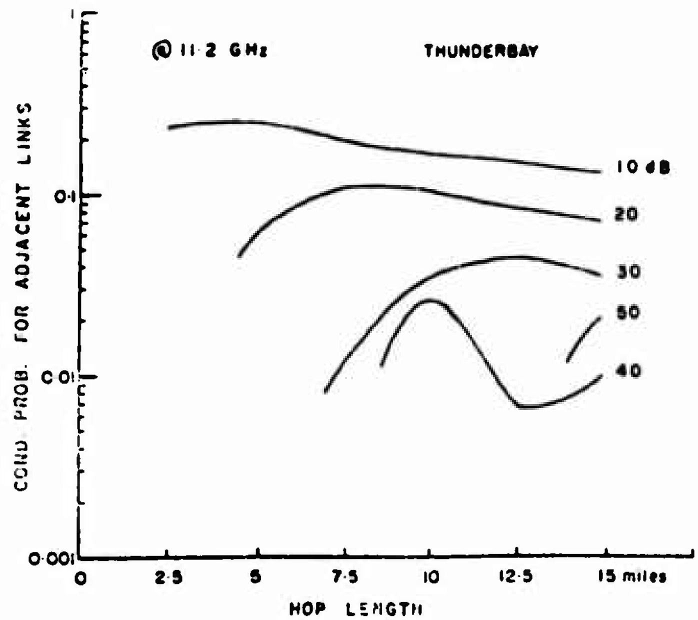
Figs. 73,74,75 (Left; Below Left; Below Right). Probability of exceeding a given attenuation at 11.2, 12.7 and 18.7 GHz for various hop lengths. The curves are obtained averaging 10 years of data.

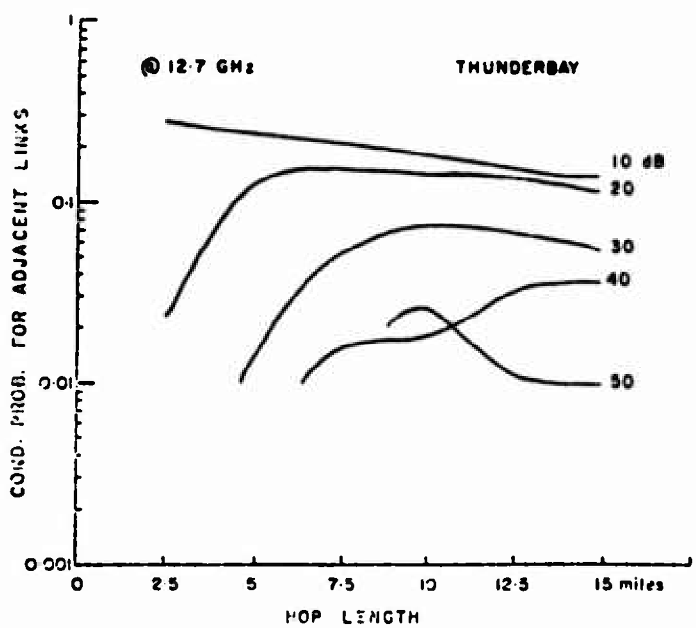


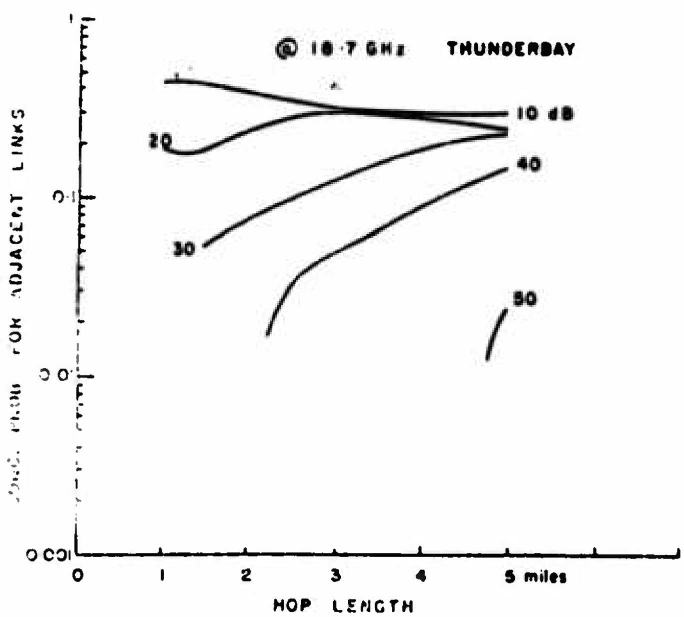


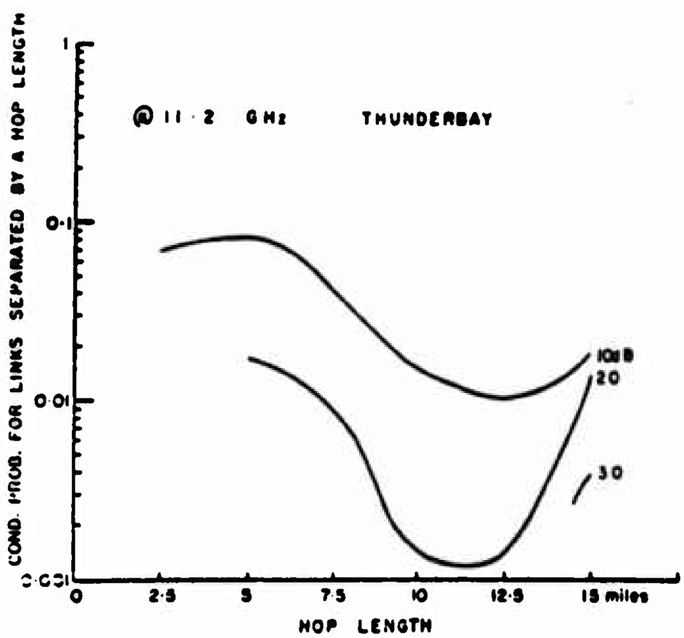


Figs. 76,77,78 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on adjacent links at 11.2, 12.7, and 18.7 GHz.

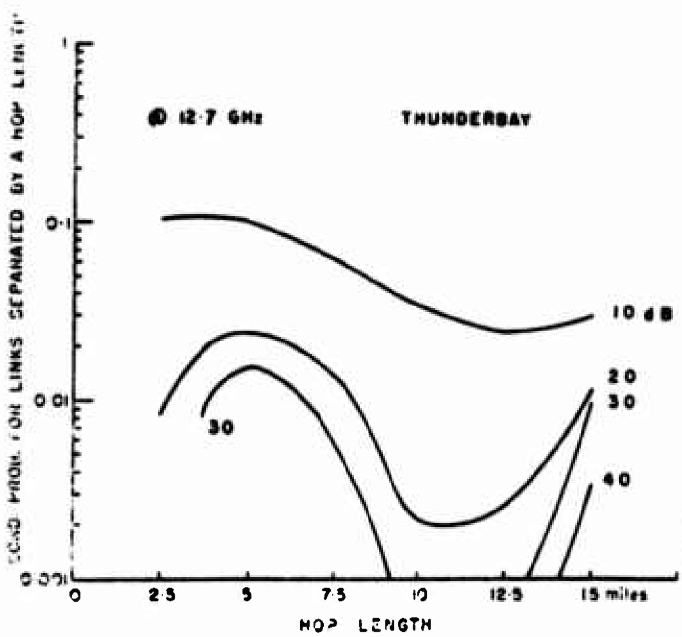


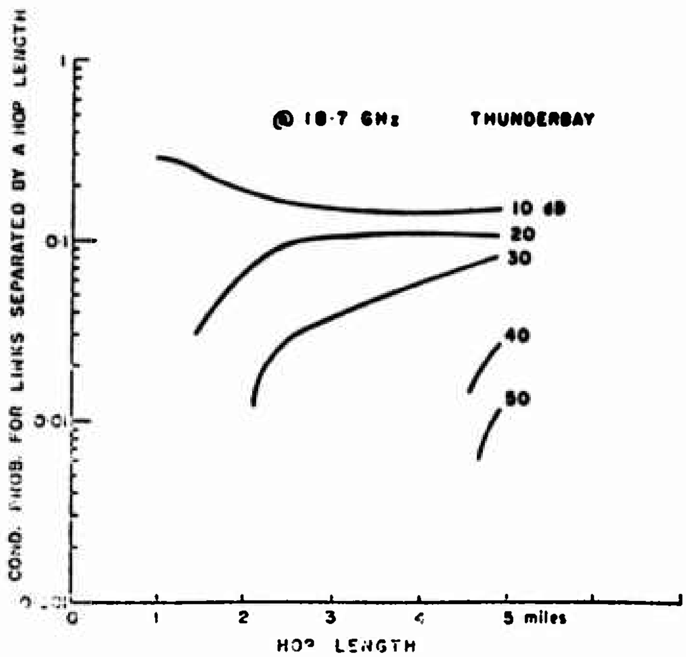






Figs. 79,80,81 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on two links separated by a hop length at 11.2, 12.7 and 18.7 GHz.





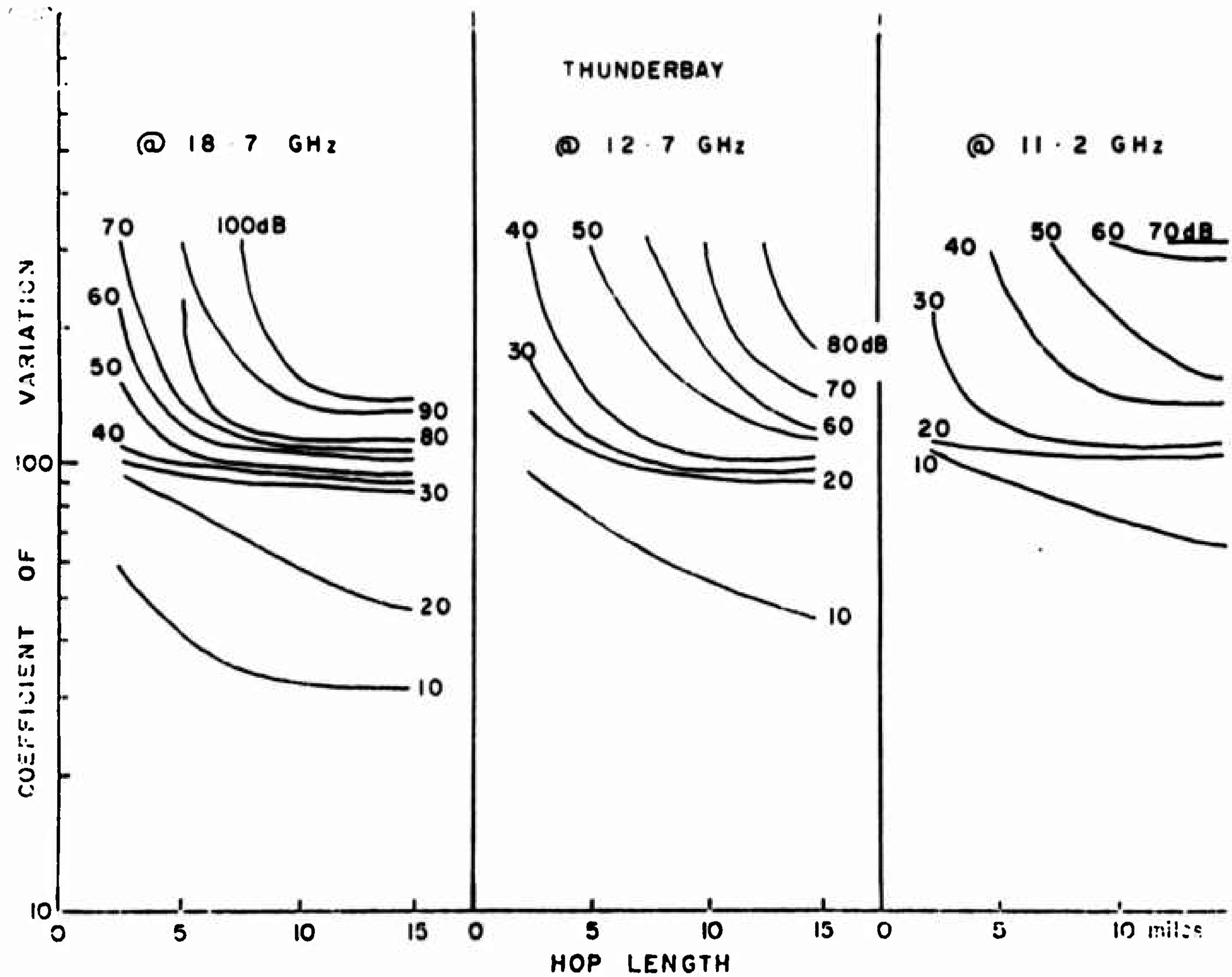
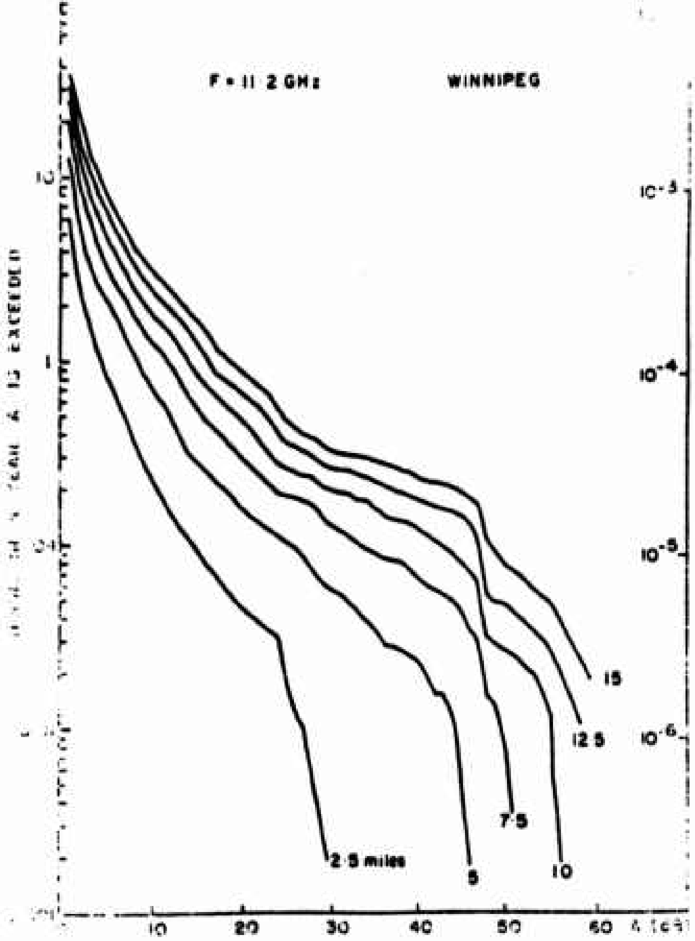
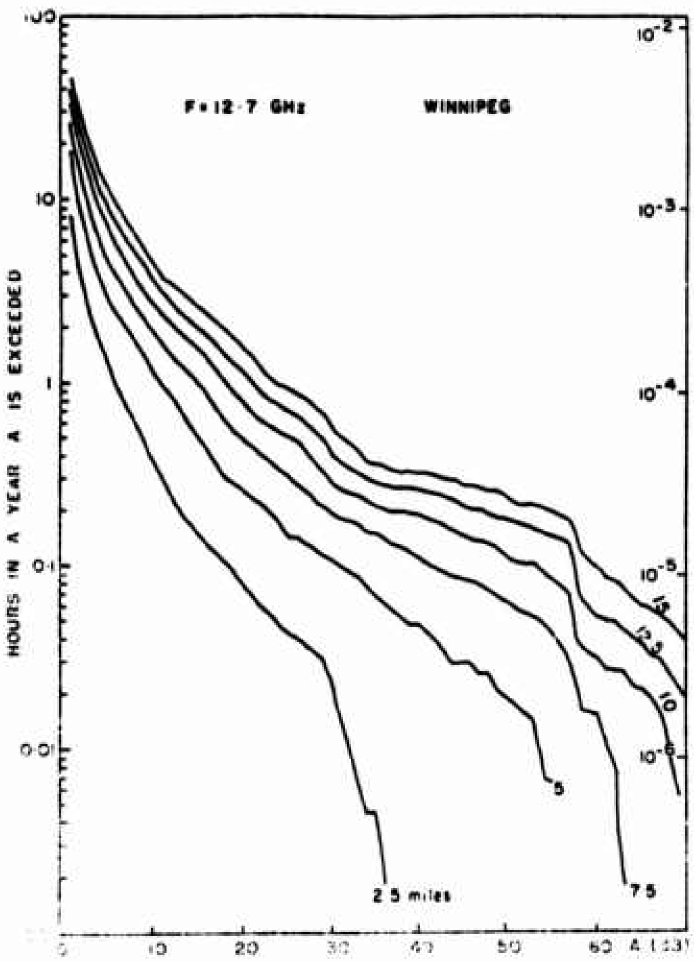
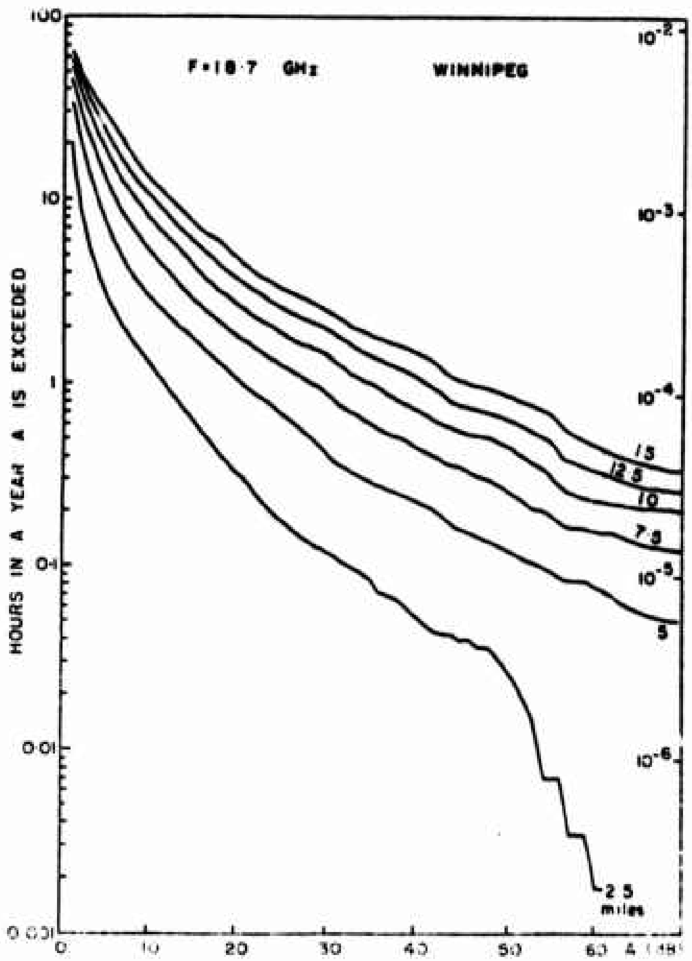


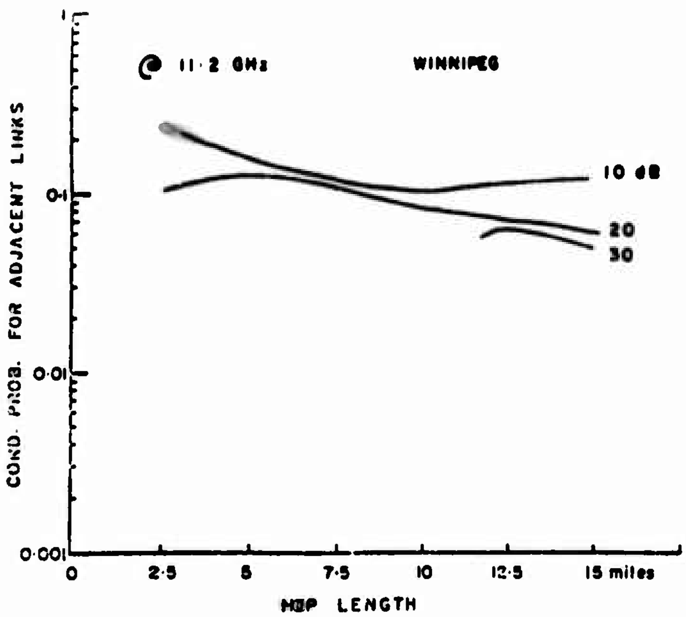
Fig. 82. Coefficient of variation of the yearly probability that a given attenuation is exceeded versus hop length for 11.2, 12.7 and 18.7 GHz.

Figs. 83,84,85 (Left; Below Left; Below Right). Probability of exceeding a given attenuation at 11.2, 12.7 and 18.7 GHz for various hop lengths. The curves are obtained averaging 10 years of data.

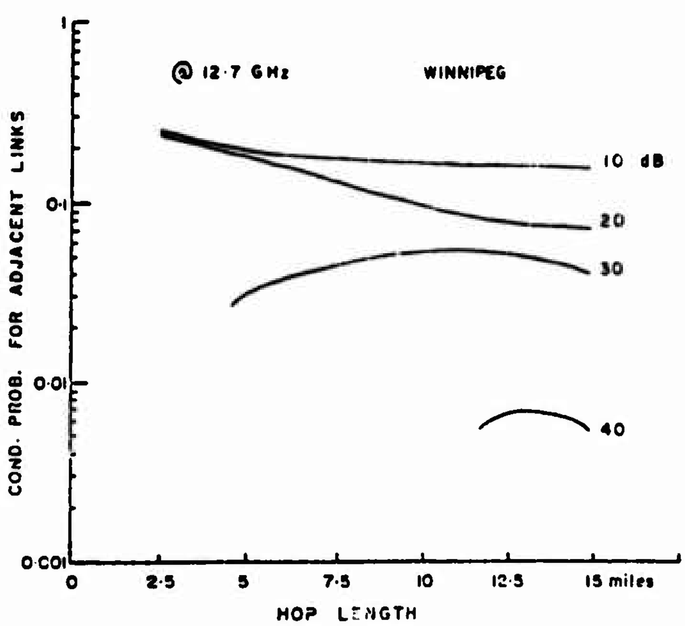


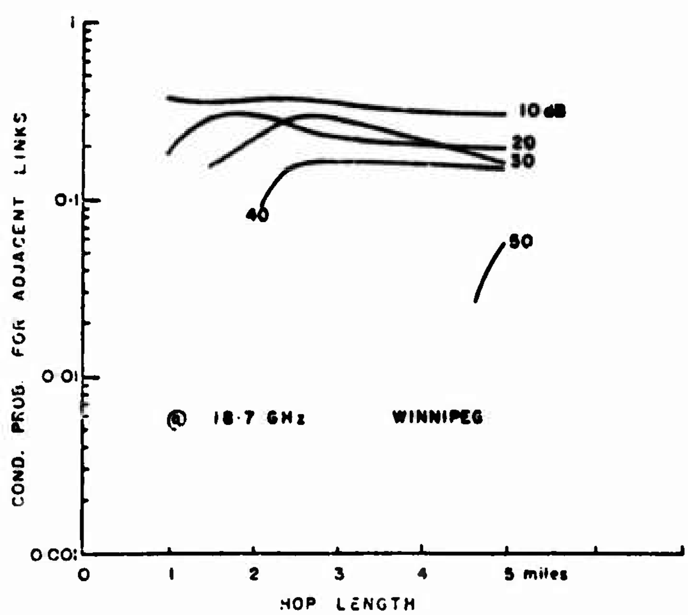


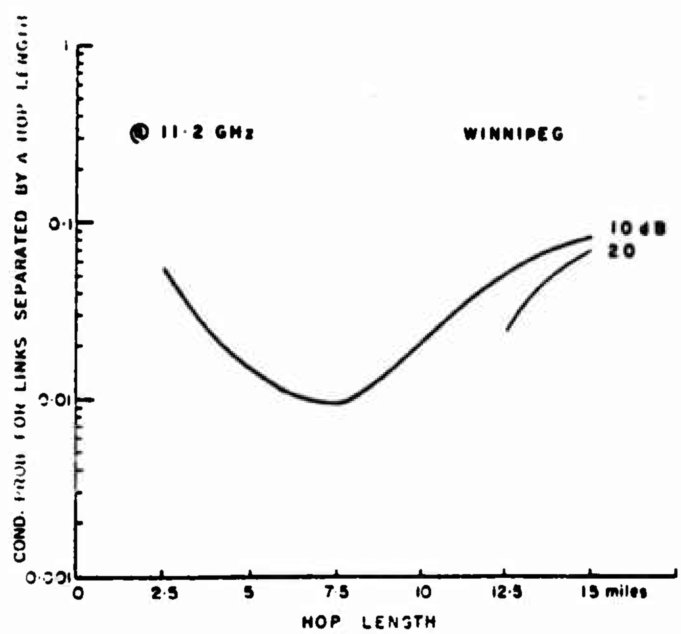




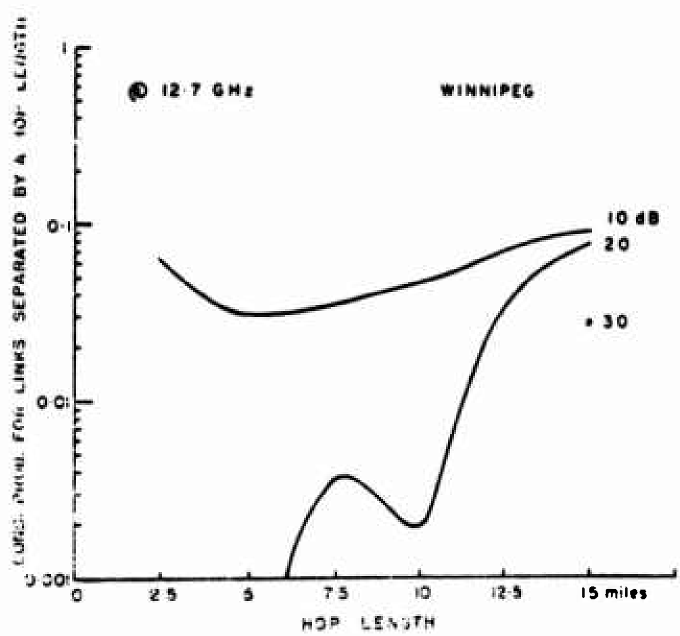
Figs. 86,87,88 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on adjacent links at 11.2, 12.7 and 18.7 GHz.

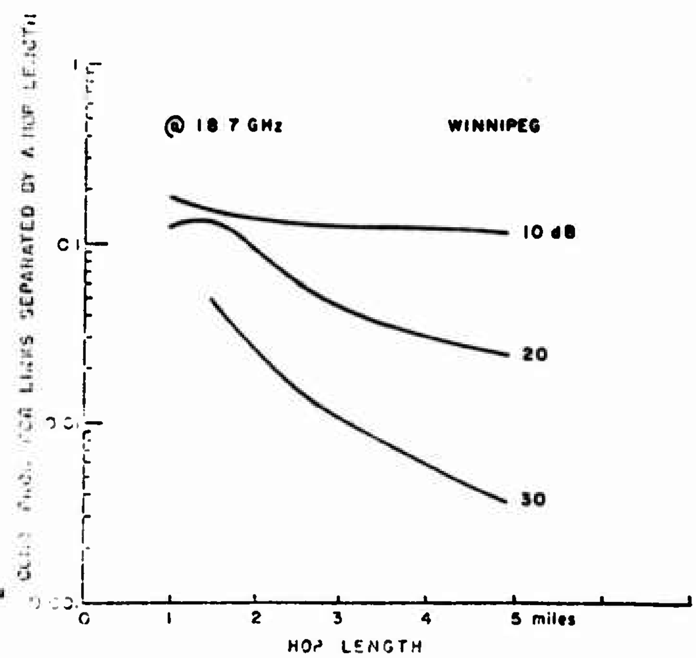






Figs. 89,90,91 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on two links separated by a hop length at 11.2, 12.7 and 18.7 GHz.





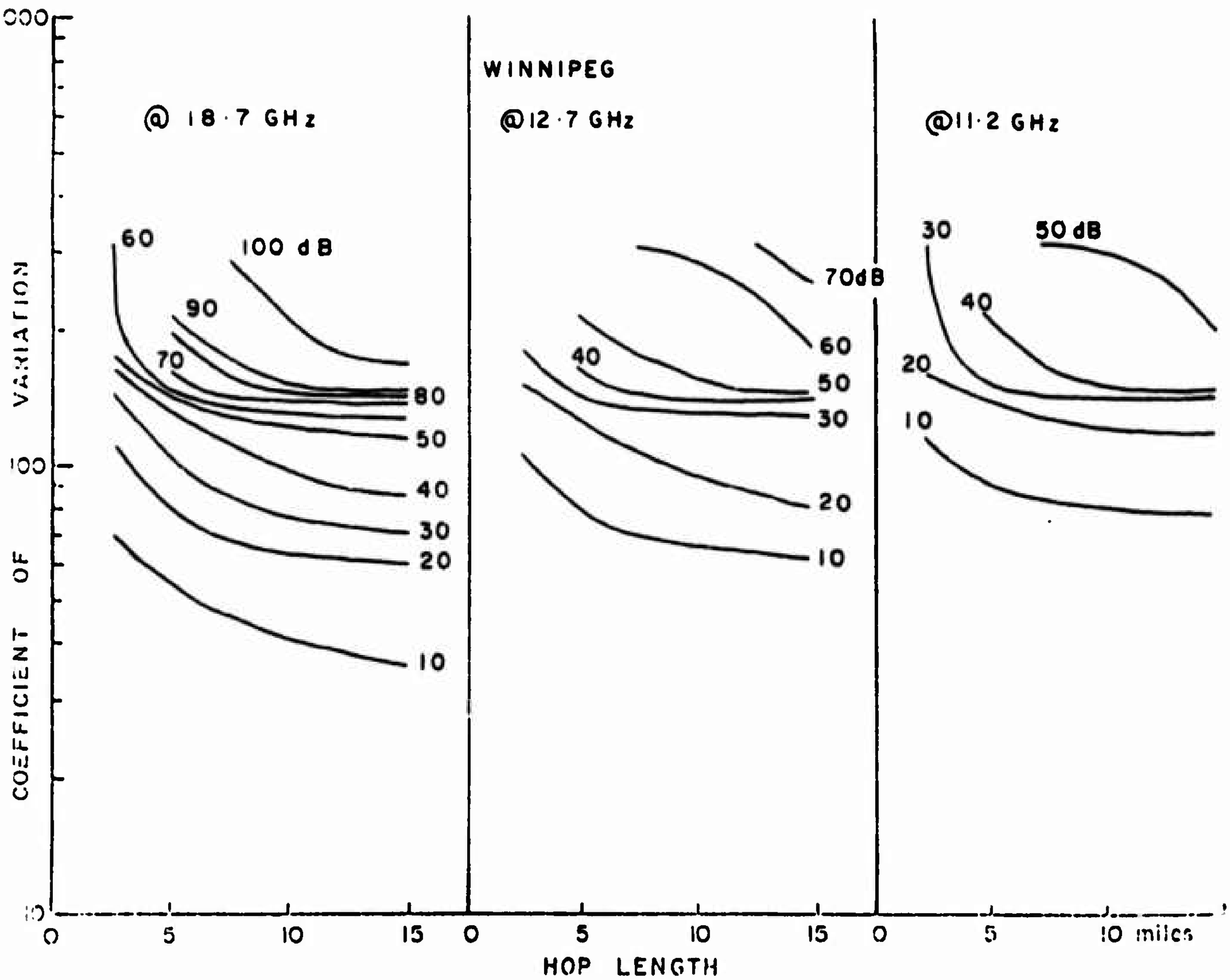
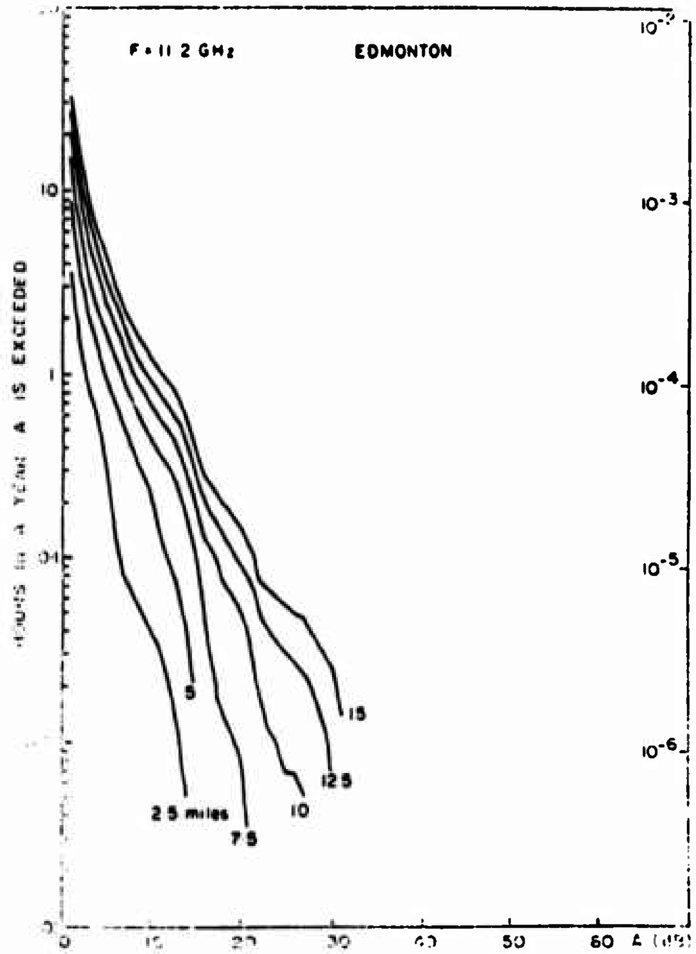
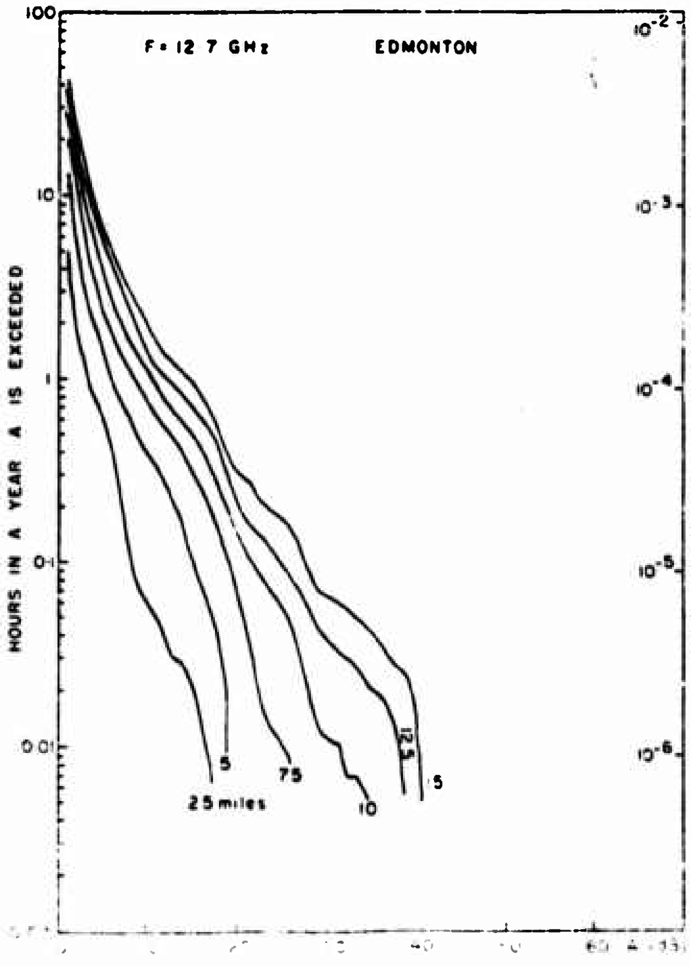
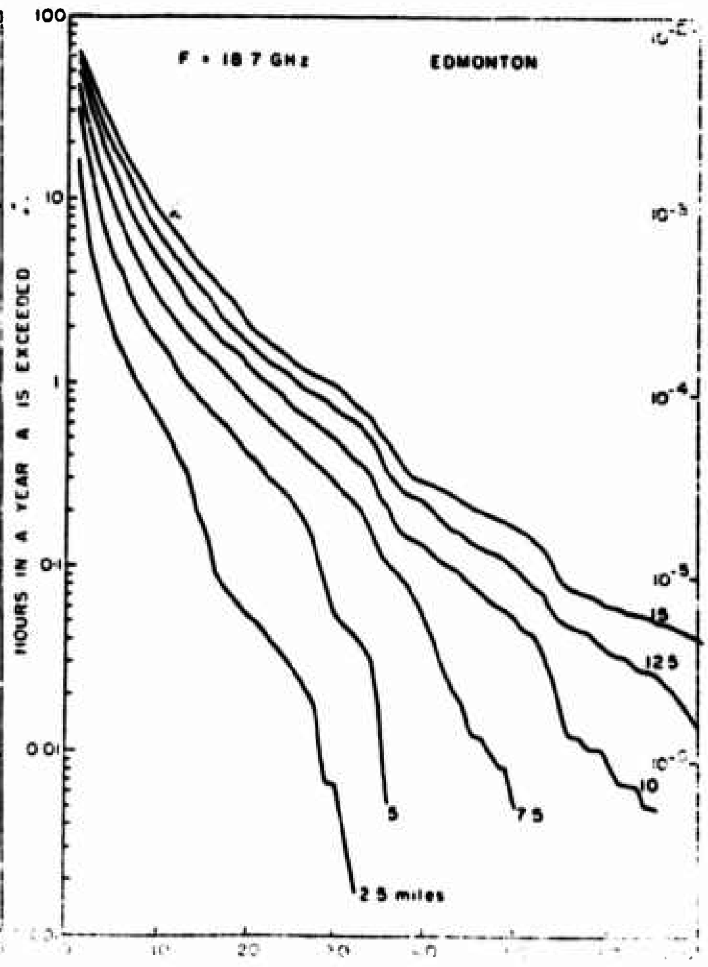


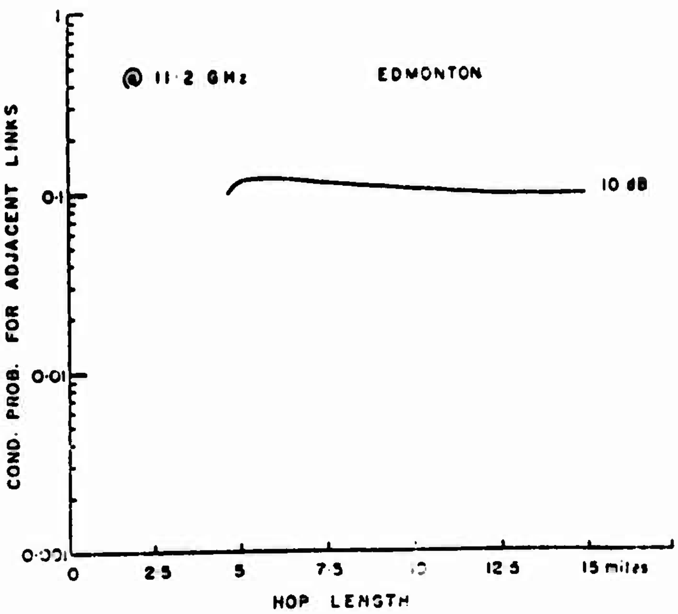
Fig. 92. Coefficient of variation of the yearly probability that a given attenuation is exceeded versus hop length for 11.2, 12.7 and 18.7 GHz.



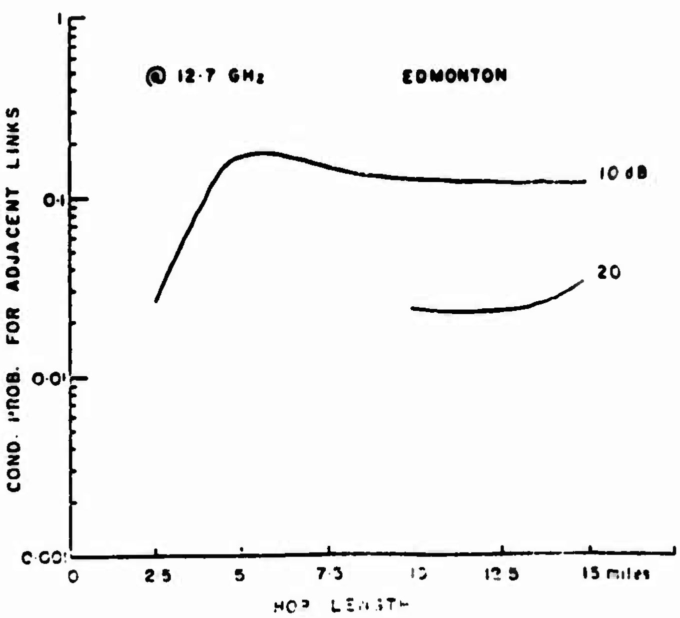
Figs. 93,94,95 (Left; Below Left; Below Right). Probability of exceeding a given attenuation at 11.2, 12.7 and 18.7 GHz for various hop lengths. The curves are obtained averaging 10 years of data.

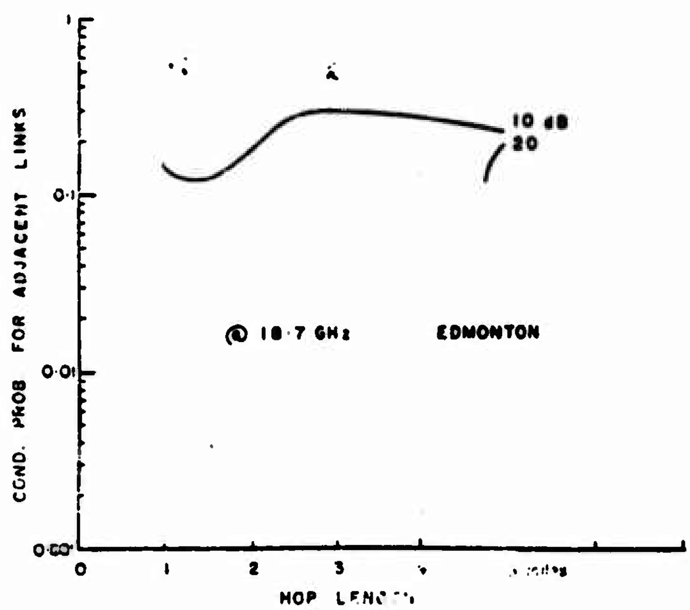




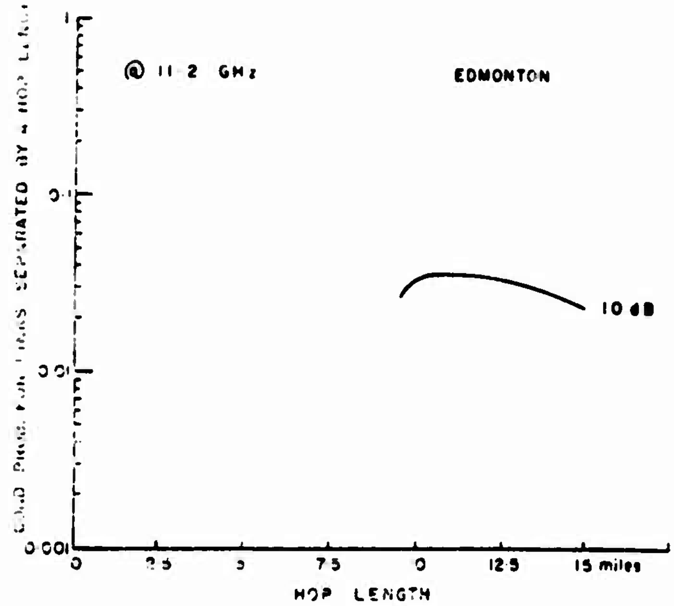


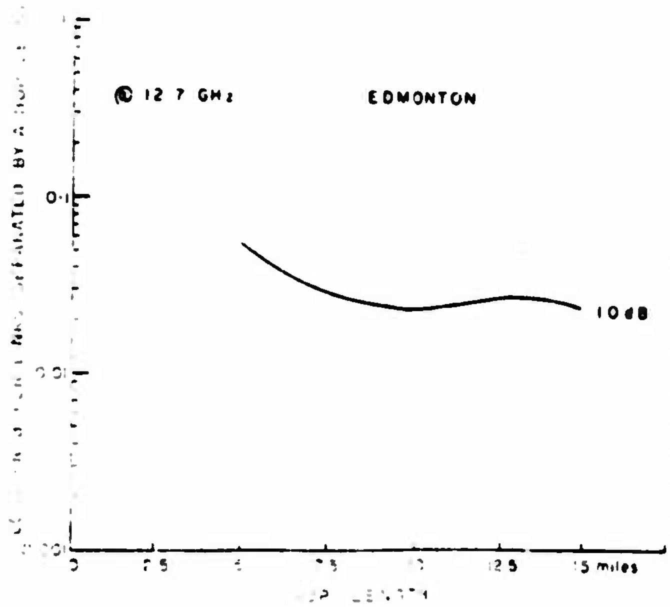
Figs. 96,97,98 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on adjacent links at 11.2, 12.7 and 18.7 GHz.

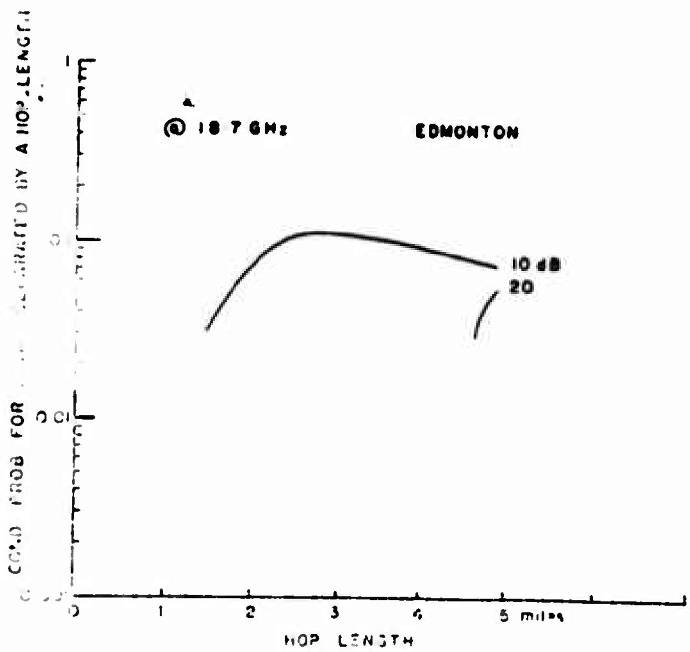




Figs. 99,100,101 (Left; Below Left; Below Right). Conditional probability that a given attenuation is exceeded contemporaneously on two links separated by a link length at 11.2, 12.7 and 18.7 GHz.







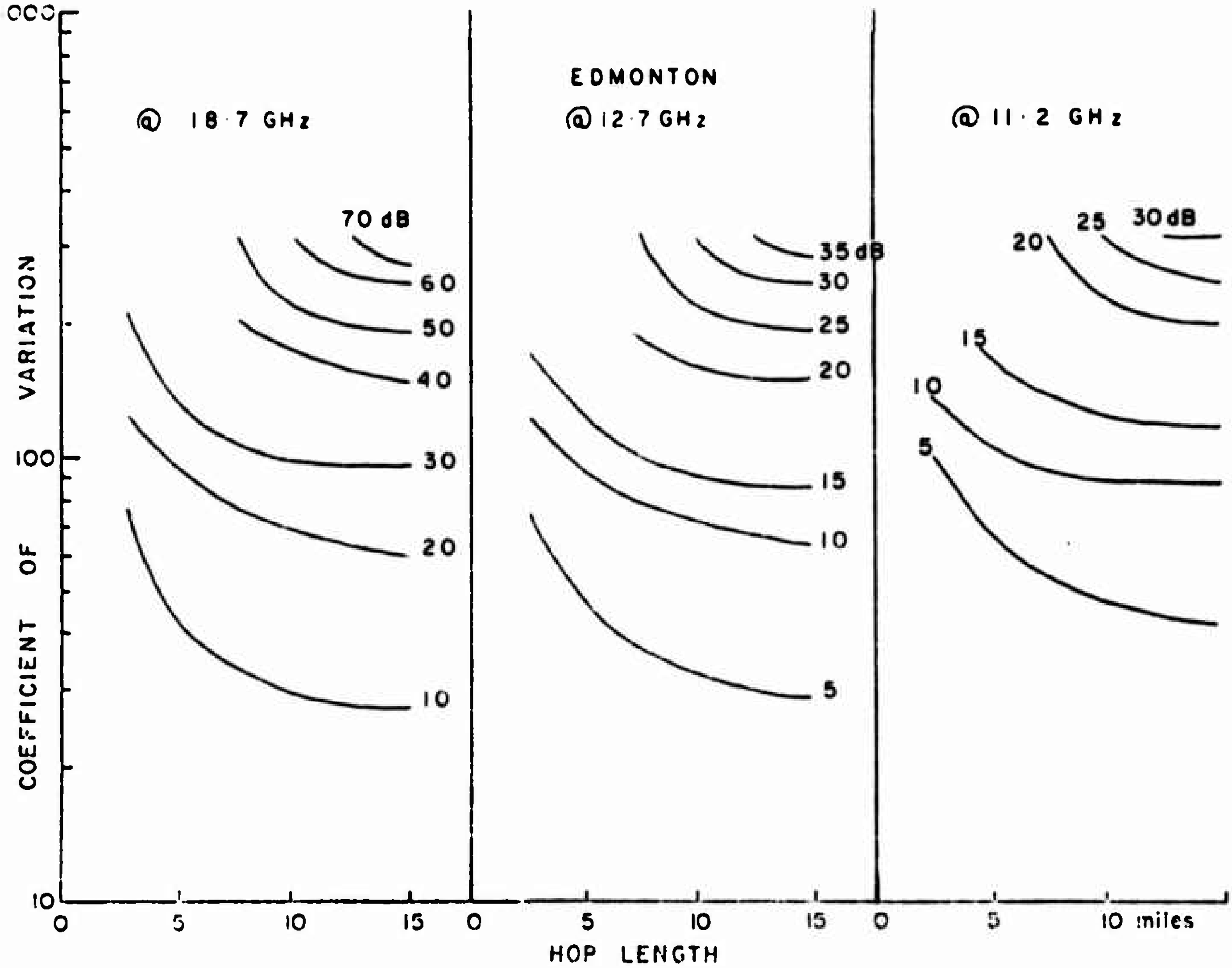


Fig. 102. Coefficient of variation of the yearly probability that a given attenuation is exceeded versus hop length for 11.2, 12.7 and 18.7 GHz.

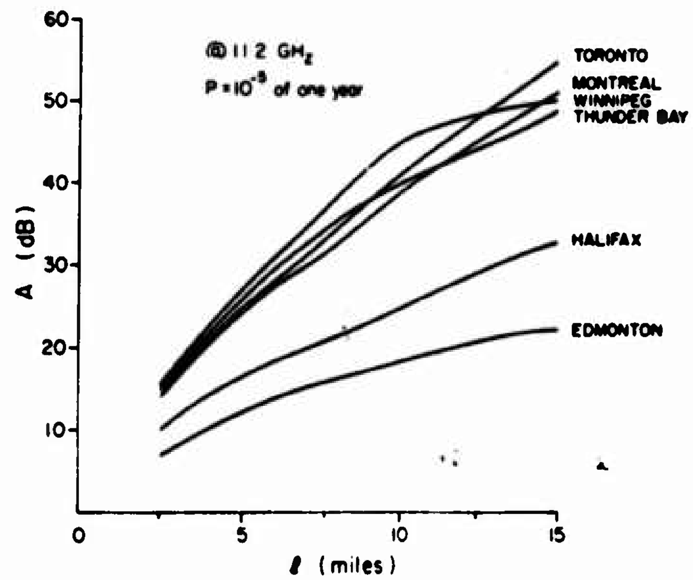


Fig. 103. Attenuation exceeded at 18.7 GHz for a probability of 10^{-5} of one year in function of hop length for the various locations.

TABLE I

Frequency (GHz)	k	α
11.2	0.02304	1.24
12.7	0.0342	1.20
18.7	0.0977	1.10

TABLE II

Raingauge	Attenuation (dB)	No. of occurrences	Individual duration (mins)	Total duration (mins)
Raingauge No. 2	5	5	13,13,9,37,7	79
"	10	4	8,11,6,27	52
"	15	1	18	18
"	20	1	8	8
"	25	1	2	2
Raingauge No. 3	5	7	6,27,10,1,11,37	102
"	10	3	8,23,8	39
"	15	2	4,9	13
"	20	-	-	-
"	25	-	-	-
Link	5	15	1,1,4,13,8,2,42 1,2,7.7,1,2,2,2	95
"	10	6	3,7,1,27,5,6	48
"	15	5	4,1,5,2,3	15
"	20	1	1	1

DURATION OF FADE HISTOGRAM FOR: MONTREAL, 1961 TO 1970 FREQ = 11.20 LINK LENGTH = 2.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	5	4	2	1																
2	7	2	6	1																
3	19	11	2																	
4	9	9	3	1																
5	14	2	1																	
6	13	3	1																	
7	8	1																		
8	10																			
9	2	1																		
10	3	2																		
11		2																		
12	1	2																		
13	1																			
14	2																			
15	2																			
16	1																			
17	1																			
18	1																			
19																				
20	2																			
21																				
22	1																			
23																				
24	1																			
25																				
26																				
27																				
30																				
35																				
40																				
45																				
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE IV

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	2	5	4		1	1														
2	2	2	1	2	1	1														
3	6	5	2	1																
4	7	3	3	3	1	1														
5	8	6	3	2	1															
6	6	5	1	2																
7	10	7	2	1	1															
8	8	12	4		3															
9	9	1	2	1	1															
10	18	4	2	1																
11	6	3	1	1																
12	10	1	1	2																
13	7		3																	
14	3	1	1																	
15	3	3																		
16	4		2																	
17	5	1	1																	
18	2	1																		
19	1																			
20	2	1																		
21	3	1																		
22		1																		
23		1																		
24	1																			
25		1																		
26	2																			
27	3																			
30	2	1																		
35	1																			
40		1																		
45	1																			
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE V

DURATION OF FADE HISTOGRAM FOR: MONTREAL, 1961 TO 1970   FREQ = 11.20   LINK LENGTH = 7.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	1	2	2		1	2		1												
2	3		2																	
3	5	1		3	2	1														
4	2	1	2	2	1		1	1												
5	5	1	1		1	1														
6	2	2	3	1		1	1													
7	3	4	5	1	1	1	2													
8	9	1	1	2	4															
9	6	5	2	1	1	1	1													
10	8	5	4	4																
11	5	7	2	1		1														
12	9	12	4		2	1														
13	7	3		2																
14	5	6		1		1														
15	11	1	1	2	1															
16	11	4	2		1															
17	6	2	2																	
18	5	1		2																
19	3		1	1																
20	3	2			1															
21	5	2																		
22	2		1																	
23	4	1	1																	
24	1																			
25	2		2																	
26	3	1																		
27	3																			
30	4	6	1	1																
35	6		1																	
40	4	1																		
45	1	1																		
50	1																			
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE VI

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	3	2	2	1	2	1														
2	2		2	1		2			1											
3	2			2	1			1	1											
4	1	1				1			1	1										
5	4	1	4			2														
6	3	1	2	2			2	1	1											
7	4	1	1	3	1	1		1												
8	1	1	1	2				2												
9	3		4		2															
10	4	3	3	1	2		2													
11	7	3	2			3														
12	9	1		2	1	2														
13	7	2	2	2	1		2													
14	3	3	6	2	1															
15	4	8																		
16	5	8	5	1	1															
17	7	5		1	1	1		1												
18	5	4	1	2	1	1														
19	7	3	1	1																
20	7	1	1		1		1													
21	9	2	3		1															
22	5	1	1																	
23	5	3				1														
24	2	1		2																
25	5	2		1																
26	4	1	1																	
27	2	1		1																
30	11	5	3	1	2															
35	10	4	2	1																
40	7	2	1																	
45	3	1																		
50	3	2																		
55	2																			
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE VII

DURATION OF FADE HISTOGRAM FOR: MONTREAL, 1961 TO 1970 FREQ = 11.20 LINK LENGTH = 12.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	3	1	1	2	2	1					1									
2		1			1						1									
3	3	1	1	1																
4	5	1	1	1						2	1									
5	3	1							1											
6	4		2	3		1			1											
7	2	1			1			1		1										
8	2	1		1		1		1												
9	1	3	1	1	1	3			2	1										
10	3	2	3	1		1														
11	4	1		2	1	1														
12	3	1	2	2				2												
13	1	1	3	1	1			1												
14	6	2	5	1	1		2	1												
15	3	3	1	1	2															
16	9	2		2		1														
17	5		1		2	2														
18	3	3	5	2	1		1													
19	5	8	2	1			1													
20	2	3	3																	
21	10	5	1	1	1				1											
22	5	5	1	1																
23	6	5	1	2	1	2														
24	5	2	1					1												
25	4	1	1	1	1		1													
26	6	2	2																	
27	6	4			2		1													
30	16	4	3	3	1	2														
35	15	6	4	2																
40	10	5	1	1	1															
45	8		1																	
50	2	2	1																	
55		2																		
60	5																			
65	3	1																		
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE VIII

DURATION OF FADE HISTOGRAM FOR: MONTREAL, 1961 TO 1970 FREQ = 11.20 LINK LENGTH = 15.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	7	4	2	1	1	2	1			1	1									
2	1						1													
3		4		1																
4		1	1	1		1					1									
5	4	1																		
6	1	2								1	1									
7	3	1	1		1					1										
8	5		1			1														
9	3	1	1	3	1	1	1													
10	1	2										1								
11	3		1	2						2										
12	3	1	1	1	1	1														
13	1	2	2	1					1											
14	1		2	1		3			2											
15	3	2	1	2	1			1			1									
16	1	1	3		1			1												
17	6	2	1		1	1	1													
18	4	1	4	3		2	1													
19	3	4	1	3	1				1											
20	6	3	1		2			2												
21	3		2		2	1														
22	6	4	2	2	1	1		1												
23	4	7	4	1						1										
24	3	1	3	2	1		1													
25	5	4	2				1													
26	7	8		1					1											
27	6	1	2	1																
30	19	12	4	2	3	3	2	1												
35	15	5	3	3	2	1														
40	13	8	4	1																
45	9	2		2	1															
50	6	2	2																	
55	4	1																		
60	2	2	1																	
65	1	1																		
70	6																			
75	1																			
80	3	1																		
85	1																			
90																				
95																				
100	1																			
105																				
110																				
115																				
120																				

TABLE IX

DURATION OF FADE HISTOGRAM FOR: HALIFAX N. S. 1962 - 1971 FREQ = 11.20 LINK LENGTH 2.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	4	1		1																
2	[illegible]	2	1	1	1															
3	7	1	1	2	1	1														
4	7	3	2																	
5	4	1	1																	
6	8	3																		
7	4	1																		
8	2																			
9	4																			
10	2																			
11																				
12																				
13	1																			
14	1																			
15	3																			
16																				
17																				
18																				
19																				
20																				
21																				
22																				
23																				
24																				
25																				
26																				
27																				
30																				
35																				
40																				
45																				
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE X

DURATION OF FADE HISTOGRAM FOR: HALIFAX N. S. 1962 - 1971 FREQ = 11.20 LINK LENGTH = 5.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1		3	1	1																
2	7	3	2	1																
3	4	4	1			1														
4	9	1	1	1		1														
5	6	3	3																	
6	4	6	1		1	1														
7	12	3	1	2	2															
8	7		1																	
9	4	4	1	1																
10	10	1																		
11	7	3																		
12	2	1																		
13	3	1																		
14	2	2																		
15	3																			
16	4																			
17	2	2																		
18	1																			
19	2																			
20	1																			
21																				
22																				
23																				
24																				
25	1																			
26	3																			
27																				
30	3																			
35	1																			
40																				
45																				
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XI

DURATION OF FADE HISTOGRAM FOR: HALIFAX N. S. 1962 - 1971 FREQ = 11.20 LINK LENGTH = 7.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	7			2				1												
2	3	1																		
3	2	2	1																	
4	5	2	1	1																
5	4	2	1																	
6	2	1	1	1																
7	6	2	1	1			1													
8	7		1	1		2														
9	7	2	2																	
10	7	3	1	1	2	1														
11	8	2	2	1																
12	9	3	2		1															
13	4	3		1																
14	3	1	2																	
15	3	2	2																	
16	4	2																		
17	8	3																		
18	4	1	1																	
19	5	1																		
20	2	1	1																	
21	4																			
22	3	1																		
23	2																			
24	1	1																		
25	2	1																		
26	1																			
27	1	1																		
30	1	1																		
35	3																			
40	4																			
45	1																			
50																				
55																				
60	1																			
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XII

DURATION OF FADE HISTOGRAM FOR. HALIFAX NO 3[illegible] 1962 - [illegible]   FREQ - 11[illegible]   LINK LENGTH - 10.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1		1					1													
2	6	1		1					1											
3	4	1			1															
4	1			1																
5	7	1	2																	
6	4	2		1				1												
7	1	1	2																	
8	3	3	2	1																
9	1	2																		
10	9		2	2			1													
11	8	4				1														
12	6	1	2																	
13	8		1	3	1	2														
14	8	6	2	1	1															
15	9	1	1																	
16	3		1	1																
17	9	4			1															
18	6	3	1	1																
19	1																			
20	3	1	2																	
21	9	3	2																	
22	1	1																		
23	5	1																		
24	4		1																	
25	4																			
26	4	1																		
27	3	3	2																	
30	9	2	1																	
35	7	2																		
40	2	2																		
45	2																			
50	1																			
55	3																			
60																				
65	1																			
70	1																			
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XIII

DURATION OF FADE HISTOGRAM FOR: HALIFAX N. S. 1962 - 1971 FREQ = 11.20 LINK LENGTH = 12.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	5		2	1																
2	2		2																	
3	6																			
4	4	1		1																
5	2						1		1											
6	4	1		1																
7	3			1	2															
8	5																			
9	2		1		1															
10	4	2						1												
11	4	2																		
12	6	2	2	1																
13	1	2	1	1			1													
14	5	2	2	2																
15	8	4	1																	
16	5	1	1			2														
17	10	2	1	1	2															
18	6	4	1	2		1														
19	9	3	2																	
20	6			1																
21	1	3	2																	
22	6	3		1	1															
23	5	2		1																
24	2		1																	
25	2	2	2	1																
26	7	1	1																	
27	4	1																		
30	16	3	3																	
35	11	4	3																	
40	3	2																		
45	1	4																		
50	4																			
55	1																			
60	4																			
65	2																			
70	1																			
75	1																			
80	1																			
85																				
90																				
95																				
100																				
105																				
110																				
115	1																			
120																				

TABLE XIV

[illegible] FREQ = [illegible] LINK LENGTH = 15.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	4				1															
2	1	1																		
3	2	2																		
4	4																			
5	3	1			1															
6	2	1			2															
7	1	3																		
8	1		1																	
9	1		1						1											
10	3						1													
11	3	2			1															
12	4		2		2															
13	4	1			1															
14	3			3				1												
15	5	2	2	1																
16	4	2	1	2																
17	5	3					1													
18	8	2		1																
19	6	1	2			1														
20	3	2	2	2	2	1														
21	7	3	2	1																
22	4	3																		
23	5	2	2			1														
24	4	2	1	2																
25	5	3																		
26	4	1	1		1															
27	5	1		1																
30	16	6	5	2																
35	18	3	2	1																
40	12	2	2																	
45	5	3	2																	
50	5	4																		
55	4	2																		
60	3																			
65	1	1																		
70	3																			
75																				
80	2																			
85																				
90	1																			
95	2																			
100																				
105																				
110	1																			
115																				
120	3																			

***** END OF OUTPUT *****

TABLE XV

DURATION OF FADE HISTOGRAM FOR: TORONTO ONT. 1962-1971 FREQ = 11.20 LINK LENGTH = 2.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	6		5	1	2		1													
2	4	6	2	2	2	2														
3	13	6	3	1	1															
4	10	5	2	1																
5	15	6	1	2																
6	8	3	1																	
7	9	2	1																	
8	2	1																		
9	3																			
10	4																			
11	2	1																		
12																				
13	1	1																		
14	1																			
15	1																			
16																				
17		1																		
18																				
19																				
20																				
21																				
22	1																			
23																				
24	1																			
25																				
26	2																			
27																				
30																				
35	1																			
40																				
45																				
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XVI

[illegible] TORONTO UNI. 1962-1971 FREQ = 11.20 LINK LENGTH = 5.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	1	1	4	2	1															
2	1	2		2	1			1	1	2										
3	2	2	2		2	1		1												
4	6	5	1		2		1		1											
5	7	4	[illegible]	1	1		1	1												
6	9	2	2	2	1	1														
7	7	6	3	2	1	2	1													
8	7	6	2	1	1															
9	10	5	3	1	1															
10	10		2																	
11	12	3																		
12	8	1																		
13	7	3																		
14	4	1		1																
15	1																			
16	2	1		2																
17	4			1																
18																				
19	1		1																	
20																				
21	1																			
22		1	1																	
23	1		1																	
24		1																		
25																				
26			1																	
27	1	1																		
30	1																			
35		1																		
40	2	1																		
45	1																			
50	1																			
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XVII

DURATION OF FADE HISTOGRAM FOR: TORONTO ONT. 1962-1971 FREQ = 11.20 LINK LENGTH = 7.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	2		1	1	1	1			1											
2	1	1		1		1	1													
3	1	5	1		2															
4	5	3	1	1							1	1	1							
5	3	2	2				1		1	1										
6	2	1	3					1			1									
7	2	1	3	1	2	1	1	1		1										
8	1	4	2		2															
9	11	6		2	1	1	1	1	1											
10	8	1	2	2	1															
11	6	6	4			2	1													
12	5	5		1	1															
13	6	1		1		1														
14	13	4	2			1														
15	3		1	1																
16	8	1	2																	
17	8	3	1			1														
18	5		1																	
19	4	3																		
20	6	1			1															
21	1				1															
22	3				2															
23	2			1																
24	1																			
25	1			1																
26			1	1																
27		2																		
30	3	1	2	1																
35	3	1	1																	
40	1	1	1																	
45		1																		
50	1	1																		
55	1																			
60	1																			
65																				
70																				
75																				
80																				
85																				
90	1																			
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XVIII

DURATION OF FADE HISTOGRAM FOR. TORONTO [illegible]

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	1															1				
2	2	2	1	1			1		1											
3	1					1														
4	3	1			1			1							1					
5	2	2	1			1			1											
6	1	1	2	2	1	2	1							1						
7	3	1		1		1			1		1		1							
8	1	2							1	1										
9	3	6	2					1				1								
10	3	1	4				1				1									
11	3	3	4			1	1													
12	4	4		2	4	1		1	1	1										
13	6	2	1	2	1		1													
14	9	6	2	1				1												
15	7	2	3				2													
16	4	5	1	1		1														
17	5	2			2															
18	3	1	1	1	1			1												
19	7	2	1	3																
20	2	2					1													
21	8		3			1														
22	7	3	1																	
23	8					2														
24	4	3	1		1															
25	1	2				1														
26	3			1																
27	4																			
30	10	2	1		3															
35	5	1		1																
40	2		1	2																
45	3	1																		
50			3																	
55	1	2																		
60	1																			
65	1	1																		
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105	1																			
110																				
115																				
120																				

TABLE XIX

DURATION OF FADE HISTOGRAM FOR: TORONTO ONT. 1962-1971 FREQ = 11.20 LINK LENGTH = 12.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1		1				1					1							1		
2	1				1						1									
3	2		2					1												
4	2																1			
5		1								1										
6		2														1				
7	2	2			1															
8	1	1					1			1					1					
9	1	1	2	2			1													
10		1	1	2	1	4					1			1						
11	2	1				1			1	1										
12	4	3	1					1					1							
13	5	3	2	1			1	1				1								
14	2	5	3			1					1									
15	4		2		2	1			2											
16	4	2	1	3	2															
17	3	4	3	1																
18	5	2	2	1				1		1										
19	10	1		1	1		1	1												
20	5	5	1			1			1											
21	5	2		1	1															
22	5	2	1	1	1		2	1												
23			2		1		1													
24	5	2		2																
25	3			1																
26	5	3	1			1														
27	9	2	1		1		1													
30	16	7	5	1		2														
35	18	3				1														
40	3	2			3															
45	2		1	2																
50	2		1	1																
55	3	1	1																	
60		1																		
65	2	1	1																	
70																				
75	1																			
80		1																		
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120	1																			

TABLE XX

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	2			1								1								
2					1															1
3	2																			
4		1	1	1			1					1							1	
5	1	1				1		1	1											
6	1		2				1				1									
7	2		2		1			1										1		
8	3	1	1														1			
9	2	1			1					1										
10	2	1														1				
11	1	2	1																	
12				1			1				1				1					
13	4	1		1		1	1				1									
14	1		1		1	1			1	1				1						
15	1	3	3	1		1		1												
16	5	5	1			1	1						1							
17	4	3	1			2														
18	7	1			1	1			1			1								
19	2	2	1	2	1						1									
20	2	5	3	2	1					1										
21	3	2	1	1	1			1		1										
22	9	1	3																	
23	7	2	2			1	1	1	1											
24	6		1																	
25	3	4		3	2			1												
26	4	2			1		1													
27	2	1	3	1					1											
30	15	7	1	5	2	1	2	1												
35	17	9	6				1													
40	15	1				3														
45	6	2			2															
50	4			2	1															
55	2	1	2																	
60	3	1		1																
65	2	1	1																	
70	1																			
75		1																		
80			1																	
85	1																			
90																				
95		1																		
100																				
105																				
110																				
115																				
120	2																			

***** END OF OUTPUT *****

TABLE XXI

DURATION OF FADE HISTOGRAM FOR: THUNDER BAY ONT, 1962 -1971 FREQ = 11.20 LINK LENGTH = 2.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	4	4	2	3	1	1			1											
2	11	5	7	3	2		1	1												
3	19	9	4	4	1	1														
4	12	2	4																	
5	9	4		1																
6	7	1																		
7	6		1																	
8	4	1																		
9	1																			
10	2	2																		
11	3	1																		
12																				
13	2																			
14		1																		
15																				
16	1																			
17	1																			
18	1																			
19	1																			
20	2																			
21																				
22																				
23																				
24																				
25																				
26																				
27																				
30																				
35																				
40																				
45																				
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XXII

DURATION OF FADE HISTOGRAM FOR: THUNDER BAY ONT, 1962 -1971 FREQ = 11.20 LINK LENGTH = 5.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	2	7	1	1	1	2	1													
2	2	1	3	1	1	1														
3	4	3			3	1	2			1										
4	3	5	1	2	1	1														
5	9	7	1	3	5	1	1	1	1											
6	15	5	5	3	1	1														
7	10	4	1	3																
8	12	2	1	1																
9	9	4	3	2	1															
10	5	1	2																	
11	5	3		1																
12	3	2		1																
13	5		2																	
14	6		1																	
15	2																			
16	1	1	1																	
17	2		1																	
18	3	4																		
19	2																			
20		1																		
21																				
22	3	1																		
23	3	1																		
24																				
25																				
26	1																			
27	2																			
30	2																			
35																				
40																				
45																				
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XXIII

DURATION OF FADE HISTOGRAM FOR: TH'NDER BAY ONT. 1962 -1971   FREQ = 11.20   LINK LENGTH = 7.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	2	1				1	1	2				1								
2	4	1	1				2													
3	2	2			1		3	1												
4	2	5	2		2						1									
5		2	2			3														
6	6	5			1	2	1													
7	2	5	3	2	1	1	1			1										
8	7	4	1	2	1	1	1	1	1											
9	8	2	2	1	2	2	1													
10	4		1	1	2	1														
11	9	6	2	3	1															
12	6	2	1	1	1	1														
13	7	1	3	2	1															
14	6	3		1	1															
15	8	4			1															
16	4		1	1																
17	3	1		1																
18	5	1	1	2																
19	3		3																	
20	7	1	1	1																
21	3	3	1																	
22																				
23	1	2																		
24		2																		
25	3		1																	
26	3		1																	
27	1																			
30	5	2																		
35	5	1																		
40	1																			
45																				
50	1																			
55																				
60	1																			
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XXIV

DURATION OF FADE HISTOGRAM FOR: THUNDER BAY ONT, 1962 -1971 FREQ = 11.20 LINK LENGTH = 10.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	1	1	1						1	1										
2	2	3	2	1	1		1													
3	2	1							2				1							
4	3	2				1		1	2											
5	2		1									1								
6	5	3			1		3	1												
7	2	7	1				1	1												
8		1	1		2						1									
9	3	2	1			1	2													
10	6	5	1	1	1	2		1	1	1										
11	7	3		2		3	2	1												
12	3	3	1		4		1													
13	4	2	2	2		1														
14	2	2	2	2		2														
15	12	1	2	2	2	1	1													
16	1	1	4	1	1															
17	3	4	1			1														
18	5	3	1	1	1															
19	3	1		1	1															
20	3	3		1	1															
21	4			1																
22	6		1	2																
23	2	2	3		1															
24	4	1	1																	
25	3		1																	
26	1	1																		
27	6	2																		
30	9	4	1	2																
35	8	3	2																	
40	5	2																		
45	2																			
50	2																			
55	1																			
60																				
65																				
70																				
75																				
80																				
85																				
90	2																			
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XXV

DURATION OF FADE HISTOGRAM FOR: THUNDER BAY ONT, 1962 -1971 FREQ = 11.20 LINK LENGTH = 12.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1		1			1															
2	3			1						1	1									
3	2			1						1	1			1						
4	1	2	2																	
5	1	2						1	1	1										
6	1		1																	
7	3	2	1			1				1			1							
8	1	3						1	1											
9	1	4	2					2	1											
10	5	3		1			1					1								
11	5	6	1	1	3		2													
12	3	3	1	1							1									
13	7	4				3	2	1	2	1										
14	4	1		2		1		1												
15	4	2	1		4	1	2	1												
16	2	2	1	1	1		1													
17	3	2	1	2			1													
18	2	4		1	1	1														
19	10		5	1	1	2														
20	1				1	1	1													
21	2	1	1	1	1															
22	6	3	1	1	2															
23	2	2	1	1		2														
24	3	1		1																
25	5	3	2	2																
26	5	1		1	1															
27	3	2	2																	
30	11	5	4	1	1															
35	17	5	1	1																
40	5			1																
45	5	1	2																	
50	1	2																		
55	3																			
60	3																			
65	1																			
70																				
75		1																		
80																				
85																				
90																				
95	1																			
100																				
105																				
110																				
115																				
120	1																			

TABLE XXVI

DURATION OF PAUL HISTOGRAM FOR: THUNDER BAY UNI, 1962 -1971 FREQ = 11.20 LINK LENGTH = 15.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	2	1		2	1							1								
2	1	1				1	1								1					
3	4										2	1	1							
4	1	2	1																	
5	3			1					1	1										
6	3		1	2						1										
7	2			2		1					1									
8	5		1		2									1						
9	1	2	1																	
10	3	2							1	1	1		1							
11		1				1		1	1	1										
12	2	4	1					1	1			1								
13	2	3			1		1	1												
14	1	4		1	1		1	1			1									
15	4	3	1	1																
16	5	3			1	2	3	1	2	1										
17	5			2		2	1													
18	4	2	1		3			2												
19	1	2	1	1			2													
20	3	3	1	2	2	1	1													
21	3	2	1			2														
22	8	3	1	1	1	1														
23	2		2	2																
24	3	1	1		3	1														
25		3			1															
26	1	2	1	2			1													
27	8	3	2	1	1															
30	16	7	7	3	1	1														
35	15	6	3	2		1														
40	14	6	1		1															
45	8			2																
50	4	1																		
55	2		2																	
60	3	2																		
65	3																			
70	1																			
75																				
80																				
85	1	1																		
90																				
95																				
100																				
105																				
110	1																			
115	1																			
120	1																			

TABLE XXVII

DURATION OF FADE HISTOGRAM FOR: WINNIPEG MANIT. 1962 - 1971 FREQ = 11.20 LINK LENGTH = 2.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	3	4	1		1	1														
2	5	5	1																	
3	12	6	1	1	1															
4	8	1	3																	
5	11	1	1	1																
6	9	2	1																	
7	6	1			1															
8	2																			
9	2	1		1																
10	5	1																		
11	2			1																
12	1																			
13	1	1	1																	
14	1																			
15	1																			
16	1																			
17																				
18		1	1																	
19		1																		
20	3																			
21	1																			
22																				
23																				
24	1																			
25																				
26																				
27	1																			
30																				
35																				
40																				
45																				
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XXVIII

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1		1			1	1	1													
2	4	3		2																
3	3	3	3			1														
4	4	3		1					1											
5	3	1		1	1	1		1												
6	11	3			1															
7	5	3	3	2	1															
8	4	2			1															
9	2	5	4					1												
10	6	2					2													
11	10	4		1																
12	6	2		1		1														
13						1														
14	9	1																		
15	7		1																	
16		1	1		1															
17	1		1																	
18	1	1			1															
19	2	1																		
20	1	1																		
21	2	1		1																
22				1																
23		2																		
24	3		1																	
25																				
26																				
27	3		1																	
30	4	2																		
35	1																			
40																				
45																				
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115	1																			
120																				

TABLE XXIX

DURATION OF FADE HISTOGRAM FOR: WINNIPEG MANIT. 1962 - 1971 FREQ = 11.20 LINK LENGTH = 7.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	2			1					1											
2	3	1	2					1												
3	1		1	1		1	1	1												
4	2	2	2		1															
5	2	1					1			1										
6		1	2	1																
7	5	3		1		1														
8	2		1	1			1													
9	7	1		1	1															
10	3	2				1														
11	4	3	1	2	1															
12	7	2	1	2																
13	3	3	2			1			2											
14	4	2	2																	
15	4	1																		
16	4	4	2		1			1												
17	9	3	1		1															
18	4		1					1												
19	1	2					1													
20	5	1					1													
21	3			1																
22	5	1		1		2														
23	1	2																		
24	1		1																	
25	1		1		1															
26	1	1	1																	
27	4				1															
30	6	3	1	2																
35	4	1	1																	
40	4	2																		
45	2																			
50	1																			
55																				
60																				
65																				
70																				
75																				
80		1																		
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120	1																			

TABLE XXX

DURATION OF FADE HISTOGRAM FOR: WINNIPEG MANIT. 1962 - 1971 FREQ = 11.20 LINK LENGTH = 10.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1			2																	
2		1	1	1	1															
3	1			1					1											
4	1	2						1												
5	1	2	2						1											
6	4	1	1	1		1	2													
7	3	1	1		1						1									
8	2	1	2					1												
9	2		2				1													
10	1	3	2																	
11	2	1	1	1		1		1												
12	4																			
13	4	3			1															
14	5	2	1	4	1															
15	5	3	1	4																
16	3	2	1							1										
17	4	2																		
18	2	1	1				1													
19	4	1	1																	
20	3					1			1											
21	4					1														
22	4	4	2	1																
23	2	2	2						1											
24	5	4			1			1												
25	4		1		1															
26	3	1																		
27	2	3					1													
30	12	2	1	2		2	1	1												
35	9	2	2	1	2															
40	3	2	1	1																
45	6	1	1																	
50	4	2	1																	
55	2																			
60	2																			
65	1																			
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110		1																		
115																				
120	1																			

TABLE XXXI

DURATION OF FADE HISTOGRAM FOR: WINNIPEG MANIT. 1962 - 1971 FREQ = 11.20 LINK LENGTH = 12.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	1		1																	
2	2	1	1		1															
3	3	2	2		1															
4	3									1										
5	1	1		2																
6	4	1	1																	
7		1	1					1												
8		1	1	1			1													
9	2				1	1														
10	2	1	1		1				1											
11			1	1																
12	2	1						1												
13	4	2	2				1													
14	3	1	2																	
15	1	1	2			1					1									
16	5	1	1				1													
17	4	3	1	1	1															
18	2	2	2	2	1				1											
19	7	4	2	1																
20	3	3		1																
21	2							1												
22	3	2		4																
23	4	1	1																	
24	2						1			1										
25	4	1																		
26	4	1	1																	
27	1		2			1														
30	17	8	3	1	1	1		1	2											
35	6	6		1	1	1	1	1												
40	8	2	1	1	1	1	1													
45	5		3	1	1															
50	5	4		1																
55	3		1																	
60	4	1																		
65	4	1																		
70	5																			
75	1																			
80																				
85			1																	
90																				
95																				
100																				
105																				
110																				
115	1																			
120	1	1																		

TABLE XXXII

DURATION OF FADE HISTOGRAM FOR: WINNIPEG MANIT. 1962 - 1971 FREQ = 11.20 LINK LENGTH = 15.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1			2		1	1														
2	1	3			1				1											
3	1	1			1															
4	1			1	1															
5	1				1						1									
6	1		2																	
7	2		1							1										
8	3	2	1																	
9		2	1		1					1										
10	2	1						1												
11	2	2	2	2			1													
12	1	1		1		1														
13	2	1																		
14			1		1				1											
15	4							1												
16	3	2		1	1		1													
17	3	1	1																	
18	4	1	1			1														
19	2		2																	
20	3	3	1	1	1															
21	3	2	1																	
22	2	2	1	1	1															
23	5	2	2						1											
24	2	1		1							1									
25	3	1	2	1																
26	4	1	2																	
27	6	2		1			1													
30	12	3	3	4			1	1		1										
35	12	10	1		1	2			1											
40	7	3	3	2	1		1	1	1											
45	7	2	1	1		1		1												
50	5	3	1	1	1	1	1													
55	3		2		1															
60	3	4																		
65	3	1																		
70	6																			
75	3																			
80	3	1																		
85	2																			
90																				
95																				
100																				
105																				
110																				
115																				
120	3	1	1																	

TABLE XXXIII

DURATION OF FADE HISTOGRAM FOR: EDMONTON ALTA 1962 - 1971 FREQ = 11.20 LINK LENGTH = 2.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	2																			
2		1																		
3	4	1																		
4	4	2																		
5	2	1																		
6	5	1																		
7	1																			
8	3																			
9	3																			
10																				
11	1																			
12																				
13	1																			
14	1																			
15																				
16																				
17																				
18																				
19																				
20																				
21	1																			
22																				
23																				
24																				
25	1																			
26																				
27																				
30																				
35																				
40																				
45																				
50																				
55																				
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XXXIV

DURATION OF FADE HISTOGRAM FOR: EDMONTON ALTA 1962 - 1971 FREQ = 11.20 LINK LENGTH = 5.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1																				
2	2																			
3		1																		
4	1	1	3																	
5	3	1																		
6	1																			
7	2																			
8	3	1																		
9	1	2																		
10	4																			
11	5	2																		
12	4	1																		
13																				
14	1	1																		
15	4																			
16	2	1																		
17	1																			
18	1	1																		
19	1																			
20																				
21		1																		
22																				
23																				
24																				
25	3																			
26																				
27																				
30																				
35	1																			
40																				
45	1																			
50																				
55	1																			
60																				
65																				
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XXXV

DURATION OF FADE HISTOGRAM FOR: EDMONTON ALTA 1962 - 1971 FREQ = 11.20 LINK LENGTH = 7.50

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	1		1																	
2	1	1																		
3		1																		
4	1	1																		
5	1	1		1																
6																				
7	3																			
8			2																	
9	1	1	1																	
10	3	1	1																	
11	2	1																		
12	4	2	1																	
13	2																			
14	1	1																		
15	4	1	1																	
16	2																			
17																				
18	3	1																		
19	4	1																		
20	1																			
21	1	1																		
22	4																			
23	4																			
24																				
25																				
26	1																			
27		1																		
30	1																			
35		1																		
40	5																			
45																				
50																				
55		1																		
60	1																			
65	1																			
70																				
75																				
80																				
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XXXVI

DURATION OF FADE HISTOGRAM FOR: EDMONTON ALTA 1962 - 1971 FREQ = 11.20 LINK LENGTH = 10.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1	1																			
2																				
3			1																	
4					1															
5	2	1		1																
6				1																
7	1																			
8	2	2	1																	
9	2																			
10	2	1																		
11	2																			
12		1	2																	
13																				
14		2	1																	
15	3																			
16	3	1																		
17	3	2																		
18	5																			
19	3	2																		
20	1			1																
21	2		1																	
22																				
23	1																			
24	1	2																		
25	3	1																		
26	3																			
27	1																			
30	8	1																		
35	1	1																		
40	2		1																	
45																				
50	3	1																		
55	1																			
60	1																			
65		1																		
70																				
75																				
80	2																			
85																				
90																				
95																				
100																				
105																				
110																				
115																				
120																				

TABLE XXXVII

DURATION OF FADE HISTOGRAM FOR: EDMONTON ALTA 1962 - 1971 FREQ = 11.20 LINK LENGTH = 12.50

[illegible]	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1		1																		
2																				
3	1		1		1															
4	1					1														
5																				
6	2																			
7	1																			
8																				
9				1																
10	3																			
11	2	1																		
12	1																			
13																				
14	2																			
15	1		1	1	1															
16	1	2	2																	
17		1																		
18	1																			
19		1	2																	
20	3	1																		
21	2																			
22		1																		
23	4	3																		
24	3																			
25	3	1																		
26	3																			
27	1																			
30	6	4	1	1																
35	9	1																		
40	4																			
45	2	1																		
50	3																			
55	1		1																	
60	1																			
65	2																			
70		1																		
75	1	1																		
80																				
85																				
90	1																			
95	1																			
100																				
105																				
110																				
115																				
120																				

TABLE XXXVIII

DURATION OF FADE HISTOGRAM FOR: EDMONTON ALTA 1962 - 1971 FREQ = 11.20 LINK LENGTH = 15.00

MIN.	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
1																				
2																				
3	2																			
4			1																	
5	2																			
6				1																
7		1			1															
8																				
9	1		1																	
10	1																			
11																				
12	1																			
13																				
14	2			1																
15						1														
16	1																			
17																				
18	2																			
19	2																			
20			2																	
21		1																		
22	1	2																		
23	1	1	1	1																
24	1		1																	
25	1	1																		
26	2	1			1															
27	2		1																	
30	9	4																		
35	3	2	1																	
40	9	3																		
45	5	1		1																
50	5	1																		
55	2																			
60	2																			
65			1																	
70	1																			
75	3																			
80	1																			
85		2																		
90	2																			
95																				
100																				
105	1																			
110																				
115	1																			
120																				

***** END OF OUTPUT *****

TABLE XXXIX

Number of rain events in 10 years for various rainfall rates*

R(mm/hr)	10	30	50	70	90
Halifax	483	159	66	39	26
Montreal	699	335	123	76	54
Toronto	423	188	105	70	50
Thunder Bay	436	210	99	68	53
Winnipeg	460	179	92	60	41
Edmonton	286	94	38	14	11

* An event of a given rainfall rate happens when rainfall rate exceeds the given value. Unfortunately, in the same precipitation pattern this can happen more than one time.

TABLE XL

Statistical properties of the sizes of rain events for various rainfall rates. For each rainfall rate three lengths are given in km. They correspond to the 50% level (median size), the 70% level and the 90% level.*

R(mm/hr)	10	30	50	70	90
Halifax	3.2	1.5	.8	<.5	<.5
	5.5	3.4	1.9	1	.5
	13.5	7.5	4.8	2.5	1.5
Montreal	2.1	1.3	1.7	1	.7
	3.5	2.5	3.5	2.3	2
	8.5	6.5	7.3	5.5	3.7
Toronto	2.75	1.7	1.1	1	?
	4.8	3.4	2	1.5	1.3
	11.5	7.2	5.5	3.5	3.3
Thunder Bay	2.5	1.5	1.2	1	.75
	5	3.5	2.2	1.4	1.1
	12.5	7.5	6.5	5	2.8
Winnipeg	2.4	1.5	1.2	.75	.7
	4	2.5	2	1.25	1
	10	5.5	4.5	2.5	2.5
Edmonton	2.2	1.2	1	0.5	<.5
	3.9	2.6	1.6	1.1	1
	8.5	6.5	2.9	2.3	2.5

* 50% level means that 50% of the rain events are smaller than indicated.

70% level means that 70% of the rain events are smaller than indicated, and so on.

The size of an event is defined as the time for which rainfall rate was larger than a given value, multiplied by the wind velocity.

Scientific Reports (Series MW) of the Stormy Weather Group

MW-1: Effect of particle shape and secondary scattering on microwave reflections from clouds and precipitation, by Milton Kerker and Walter Hitshhfeld, March 1951.

MW-2: Measurement of snow parameters by microwaves, by J.S. Marshall and K.L.S. Gunn, May 1951.

MW-3: The modification of rain with distance fallen, by E. Caroline Rigby and J.S. Marshall, January 1952.

MW-4: Interpretation of the fluctuating echo from randomly distributed scatterers: Part I, by J.S. Marshall and Walter Hitschfeld, October 1951.

MW-5: Scattering and absorption of microwaves by a melting ice sphere, by M.P. Langleben and K.L.S. Gunn, March 1952.

MW-6: Interpretation of the fluctuating echo from randomly distributed scatterers: Part II, by P.R. Wallace, December 1951.

MW-7: The microwave properties of precipitation particles, by J.S. Marshall, T.W.R. East and K.L.S. Gunn, July 1952.

MW-8: Precipitation trajectories and patterns, by J.S. Marshall, M.P. Langleben and E. Caroline Rigby, August 1952.

MW-9: A theory of snow crystal habit and growth, by J.S. Marshall and M.P. Langleben, July 1953.

MW-10: The modification of rain in showers with time, by E. Caroline Rigby, and J.S. Marshall, March 1953.

MW-11: A mathematical treatment of random coalescence, by Z.A. Melzak and Walter Hitschfeld, March 1953.

MW-12: Errors inherent in radar measurement of rainfall at attenuating wavelengths, by Walter Hitschfeld and Jack Bordan, June 1953.

MW-13: Radar evidence of a generating level for snow, by K.L.S. Gunn, M.P. Langleben, A.S. Dennis and B.A. Power, July 1953.

MW-14: Initiation of showers in cumuli by snow, by A.S. Dennis, July 1953.

MW-15: Turbulence in clouds as a factor in precipitation, by T.W.R. East and J.S. Marshall, July 1953.

MW-16: The terminal velocity of snow aggregates, by M.P. Langleben, January 1954.

MW-17: Development during fall of raindrop size distributions, by E. Caroline Rigby, K.L.S. Gunn and Walter Hitschfeld, January 1954.

MW-18: The effect of wind shear on falling precipitation, by K.L.S. Gunn and J.S. Marshall, December 1954.

MW-19: The convection associated with release of latent heat of sublimation, by R.H. Douglas and J.S. Marshall, December 1954.

MW-20: A: Size distribution generated by a random process, by Walter Hitschfeld. B: The distribution with size of aggregate snowflakes, by K.L.S. Gunn and J.S. Marshall, September 1956.

MW-21: Pattern in the vertical of snow generation, by R.H. Douglas, K.L.S. Gunn and J.S. Marshall, July 1956.

MW-22: Precipitation mechanisms in convective clouds, by T.W.R. East, January 1956.

MW-23: Measurement and calculation of fluctuations in radar echoes from snow, by Walter Hitschfeld and A.S. Dennis, July 1956.

MW-24: The plan pattern of snow echoes at the generating level, by M.P. Langleben, February 1956.

MW-25: A possible role of hail in formation of tornadoes, by Walter Hitschfeld and J.S. Marshall, March 1957.

MW-26: Growth of precipitation elements by sublimation and accretion, by R.H. Douglas, May 1957.

MW-27: Studies of Alberta hail storms 1957, by R.H. Douglas and Walter Hitschfeld, May 1958.

MW-28: Electronic constant altitude plan position indicator for a weather radar, by T.W.R. East, November 1958.

MW-29: The motion and erosion of convective storms in severe vertical wind shear, by Walter Hitschfeld, July 1959.

MW-30: Alberta hail, 1958, and related studies. Parts I and II by R.H. Douglas, Part III by R.H.D. Barklie and N.R. Gokhale, July 1959.

MW-31: The quantitative display of radar weather patterns on a scale of grey, by T.H. Legg, June 1960.

MW-32: Weather-radar attenuation estimates from raingauge statisitcs, by P.M. Hamilton and J.S. Marshall, January 1961.

MW-33: Improvements in weather-radar grey scale, by F.T. Barath, July 1961.

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MW-34: Interim account of hail studies - November 1960, by R.H. Douglas, J.S. Marshall and R.H.D. Barklie, reprinted in April 1962.

MW-35: Alberta Hail Studies, 1961, by A.E. Carte, R.H. Douglas, C. East, K.L.S. Gunn, Walter Hitschfeld, J.S. Marshall, E.J. Stansbury, December 1961.

MW-36: Alberta Hail Studies, 1962-63, by A.E. Carte, R.H. Douglas, R.C. Srivastava and G.N. Williams, August 1963.

MW-37: Precipitation profiles for the total radar coverage, by P.M. Hamilton, September 1964.

MW-38: Two studies of convection, by R.C. Srivastava and C.D. Henry, October 1964.

MW-39: Interpretation of the fluctuating echo from randomly distributed scatters: Part 3, by Paul L. Smith Jr., December 1964.

MW-40: Facsimile and areal integration for weather radar, vols. I and II, by Marceli Wein, April 1965.

MW-41: Time-dependent characteristics of the heteorogeneous nucleation of ice, by Gabor Vali and E.J. Stansbury, April 1965.

MW-42: Alberta Hail Studies, 1964, by J. Derome, R.H. Douglas, Walter Hitschfeld, M. Stauder, July 1965.

MW-43: Attenuation of a parallel beam of light, particularly by snow, by Olav Lillesaeter, April 1965.

MW-44: Measurements of new fallen snow, by K.L.S. Gunn, August 1965.

MW-45: Measurements of falling snow, by K.L.S. Gunn and M. Wein.

MW-46: Experiments on the nucleation of ice, 1961-63, by G. Vali and E.J. Stansbury, August 1965.

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MW-48: Part I of Air Transport Association Report "Parameters for Airborne Weather Radar", by J.S. Marshall, C.D. Holtz, Marianne Weiss, December 1965.

MW-49: Alberta Hail Studies, 1966, by A.J. Chisholm, Marianne English, Walter Hitschfeld, Jerry Pell, N.H. Thyer, May 1967.

MW-50: Convective overturning and summer storms, by J.S. Marshall, January 1968.

MW-51: Measurements of snowfall by optical attenuation, by Charles Warner, and K.L.S. Gunn, November 1967.

MW-52: A preliminary microwave attenuation climatology for the Montreal area based on weather radar data, by R.R. Rogers and K.M. Rao, January 1968.

MW-53: Showers observed by stereo cameras and radar, by R.W. Shaw and J.S. Marshall, October 1972.

MW-54: Measurement of snowfall by radar, by Paul Carlson, March 1968.

MW-55: Life cycle of a summer storm from radar records, by Clifford Holtz, May 1968.

MW-56: HARPI, 1967 - The development and use of a height-azimuth-range position indicator, by I.I. Zawadzki and E. Ballantyne, February 1968.

MW-57: Alberta Hail Studies, 1967, by Jerry Pell, P.W. Summers and A.H. Paul, Gabor Vali, December 1967.

MW-58: Ice nucleation relevant to formation of hail, by Gabor Vali, December 1968.

MW-59: The hail storm of 29 June 1967, by A.J. Chisholm, Marianne English and C. Warner, March 1969.

MW-60: Further studies of the effects of precipitation on convection, by F. Ian Harris, January 1969.

MW-61: Quantitative hailstorm studies using broad vertical beam radar, by Jerry Pell, July 1969.

MW-62: Rotating-lens stereo cloud photography. by R.W. Shaw, July 1969.

MW-63: Interpretation of the fluctuating echo from randomly distributed scatterers, Part 4, by R.R. Rogers, September 1969.

MW-64: Numerical simulation of large convective clouds, by Takao Takeda, December 1969 (in two volumes).

MW-65: Showers and continuous precipitation: 25 July 1969, by Peter P. Zwack, September 1971

MW-66: Rainfall extreme value statistics applied to microwave attenuation climatology, by J.H.S. Bradley, February 1970.

MW-67: Wind measurements near Alberta hailstorms, 1966-67, by N.H. Thyer, June 1970.

MW-68: Hail research at McGill, 1956-1971, by Stormy Weather Group, W.F. Hitschfeld, ed., May 1971.

MW-69: The low level mesoscale wind field of Alberta hailstorms, by G. Ragette, September 1971.

MW-70: Pulse compression for meteorological radars, by G.L. Austin and R.W. Fetter, January 1972.

MW-71: Hail detection with a polarization diversity radar, by Brian L. Barge, February 1972.

MW-72: Photo and radar studies of Alberta storms, by C. Warner, with contributions by J.H. Renick, M.W. Balshaw and R.H. Douglas, April 1972.

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MW-73: A three dimensional numerical model of atmospheric convection, by J.T. Steiner, July 1972.

MW-74: An interpolation and extrapolation technique for precipitation patterns, by Yoondae, D. Ahn, May 1972.

MW-75: Ice nuclei and convective storms, by George A. Isaac, November 1972.

MW-76: Measurement and application of rainfall autocorrelation functions, by I.I. Zawadzki, January 1973.

MW-77: Rain attenuation studies, by G. Drufuca, March 1973 (in two volumes).

Technical Notes

MWT-1: Photography at the AN/CPS-9 weather radar at Montreal airport, by M.P. Langleben and Walter Hitschfeld, January 1955.

MWT-2: The elevation controller for CAPPI operation of the AN/CPS-9 weather radar, by C.W.R. East. Submitted under Contract No. AF19(604)-1579, October 1956.

MWT-3: An optical system for automatic synthesis of constant-altitude radar maps, by M.P. Langleben and W. Denis Gaherty, January 1957.

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